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FIFTEENTH ARCTIC AND
MARINE OIL SPILL PROGRAM
TECHNICAL SEMINAR**

**COMPTE RENDU: 15^e COLLOQUE
TECHNIQUE DU PROGRAMME DE LUTTE
CONTRES LES DÉVERSEMENTS
D'HYDROCARBURES EN MER ET DANS
L'ARCTIQUE (AMOP)**



**JUNE 10-12, 1992
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Fifteenth Arctic and Marine
Oilspill Program Technical
Seminar

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The Development and Use of Contemporary Oil Spill Models in the Preparation of a Response Plan for Cold Lake Bitumen.

by

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Abstract

A new advanced contingency plan has recently been developed for the West Coast by Esso Resources, now Imperial Oil (Resources Division), using a combination of new mapping techniques, state of the art computer models and oil-specific laboratory measurements. This work was coordinated to satisfy the demands of the contingency planner, the operational needs of both local and national spill response groups and to meet the informational requirements of crisis management. Such a united approach means that the same basic and integrally consistent information is used by all groups. Thus, during an incident response situation, all groups will have available to them the same basic sets of information.

Introduction

Since 1975, Imperial Oil Limited has produced a heavy crude oil, known as bitumen, from its Cold Lake facility located in north eastern Alberta. The current production rates are between 14,000-16,000 m³ per day. This bitumen is produced using a cyclic steam process. The reservoir is heated using steam injection in order to mobilize the flow of the bitumen, and after a suitable period of time, the oil is extracted. As produced the oil has an API gravity of 9-10, and a viscosity of about 200,000 cSt at 15°C.

In order to transport this material to market by pipeline, the produced oil is blended with a light condensate (up to 30% by volume) to produce a material with a viscosity of less than 250 cSt at temperatures as low as 0°C. This diluted material is called "dilbit" and has an API gravity of 26. Depending on market conditions, up to 15% of this production is transported by the Trans Mountain Pipe Line to Vancouver where it is loaded for shipment by sea. In recent years, approximately 10 tanker shipments of 70,000 m³ each were made per year. In addition to the shipment overseas by tanker, there is one dilbit shipment per month to Tacoma using a 18,000 m³ barge and tug combination.

Contingency Plan Development

A contingency plan is a combination of a response plan and a description of the various techniques that would be used and an identification of the environmentally sensitive areas that might be impacted by a spill. Normally contingency plans are developed based on a series of scenarios which describe typical spill situations. In many instances, extreme case scenarios are chosen in order that the contingency plan considers all possible situations. Most contingency plans are developed for a broad base of oil types and generic response methodologies which are commonly used for spill mitigation.

Since bitumen and dilbit have significantly different properties than many other crude oils and refined products, a dedicated contingency plan for dilbit has been developed by Imperial Oil Limited for the shipment from the Port of Vancouver. In order to develop a comprehensive contingency plan to respond to spills of this material during its production and transport, a series of studies of the physical properties as related to response techniques has been undertaken by Imperial Oil Limited. While standard oil industry descriptions of both bitumen and dilbit are available, new data specifically related to spill response needs have been developed. These include studies of the physical properties of the oil as a function of temperature and time (Nicholson and Brown, 1991).

Response Scenario Development

Identification of Scenarios

The selection of scenarios to be used in the development of a contingency plan is a complex and difficult process. The scenarios should be chosen to represent a variety of possible situations so that the total span of response activities can be represented. The locations should be based on those areas of high traffic density movements and identifiable navigational risks. A review of past accidents, whether the release of oil occurred or not, provides considerable guidance in the selection of possible spill sites. The selected sites are shown on a map of the area.

The amount of oil spilled is a significant parameter in the description of a scenario. Historical spill data indicates that less than 20% of a ship's cargo is spilled during an incident, and this value has been selected for the contingency planning spill scenarios. Since the size of shipping vessels for Cold Lake dilbit is well known, only four different oil release scenarios (12,000 m³ (4hr), 2,400 m³ (3hr), 1,200 m³ (4hr) and 240 m³ (2hr)) were considered.

A study of the weather conditions on the west coast of Canada was undertaken. The most difficult weather, in terms of spill response, was found to be in mid-November and thus this season was chosen for all the scenarios. By using the same time period for all situations, it is possible to directly compare the various scenarios. This work was extended to include scenarios for each of the four seasons, in order to examine the difference between various periods of the year.

Model Selection

The model selected for the dilbit scenarios was initially developed for the Firth of Forth by BP and was called SCOOP (Page and Stamp (1986) and Hill, (1983)). The first version of this model ran on a large main frame and was typical of the models of its time. Since the model was designed to run on a main frame, the input data was collected together in the form of an input matrix, and the output was in tabular form or presented as a series of printer outputs. Many of the limitations of this model were directly associated with its main frame origins. During the past eight years, the model had been modified to run on a PC computer, and the input-output routines were upgraded to meet the new environment. Changes had also been made in some of the algorithms, especially those related to evaporation and dispersion. There had been so many changes that the model had little resemblance to the original model and so when the code was transferred to a SUN engineering station, it was renamed **MOSESS** (Model of Oil Spills for ESSo). Like most oil spill models, the required input data consists of spatially and temporally variable wind and ocean current fields and the properties of the oil necessary for computation of the weathering processes.

The wind data was obtained from the Atmospheric Environment Service of Environment Canada in the form of real time hourly data for the seven years between 1981-1989. This data was extrapolated using a combination of centre of influence of the weather stations and a binomial vector smoothing system to obtain winds over the model domain. The coast of British Columbia, in the areas to be modelled, is extremely mountainous and the winds at the observing stations probably did not represent the wind occurring over the ocean in the Juan De Fuca and Georgia Straits or in the Port of Vancouver. In order to improve the model wind input data, an orographic model for winds was used. This model, initially developed by Mass and Dempster (1985), was modified for the area of the model and the winds produced were used as inputs for the oil spill model. These new wind fields were significantly different from the wind fields generated by using data from the observing stations.

Since there are very few observing stations in the area, the winds derived from observations tend to lack detail (figure 1). The effects of the

mountains on Vancouver island and on the mainland are clearly evident from the orographic calculations as shown in figure 2.

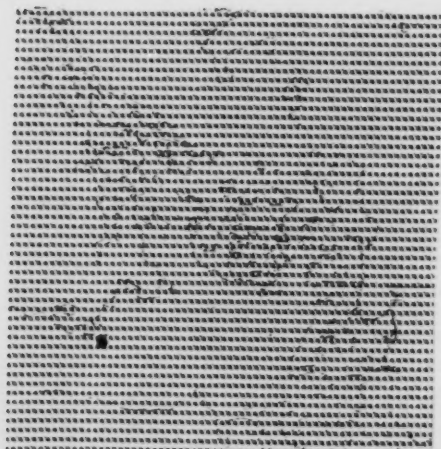


Figure 1. Winds derived from observations

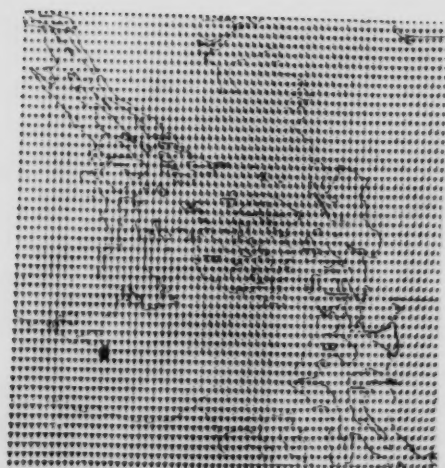


Figure 2. Winds from the orographic model

The ocean current data was taken from the Current Atlases for Juan De Fuca Strait, Georgia Strait and Vancouver Harbour (Hodgins *et al* 1991). These current atlases use a combination of model information and observations to develop typical ocean current patterns for the area. The complexity of the oceanographic regime in the area suggested that a higher resolution current data should be used. A 3-D model developed by Blumberg and Mellor (1987) at Princeton was adapted for the area. Bathymetric information from current hydrographic charts was digitized and used together with tidal data to develop a spatially and temporally variable winds field over the model regime. The use of the model was functional in the scenario development. Due to complexities of the 3-D model, the use of this procedure would not be operational for response to an actual spill situation. Data from the current atlases combined with the 3-D model would be used for emergency response needs. The current patterns from the atlas are very simple as shown in figure 3, and lack detailed structure around the Gulf islands. The more complex currents generated by the 3-D hydrodynamic model are shown in figure 4.

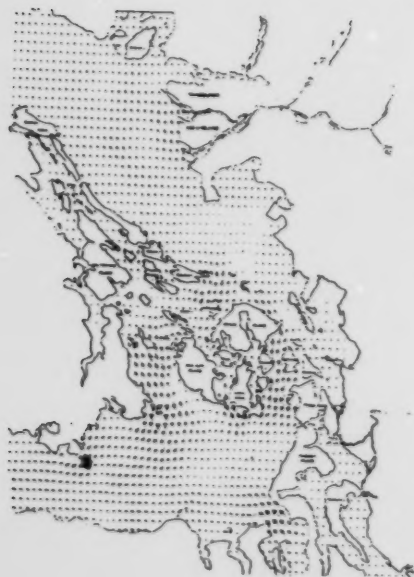


Figure 3. Currents from the West Coast Oceanographic Atlas



Figure 4. Currents generated from the 3-D hydrodynamic model

Since the physical-chemical properties of Cold Lake bitumen and the blended dilbit were so different from the light crude oils for which the model was initially developed, laboratory measurements of evaporation, density and emulsification as a function of time were used for modelling the weathering parameters.

The trajectories from a spill from the area of Race Rocks are shown in figures 5-9.

Sensitivity Mapping

There have been numerous studies of the environmental sensitivity of various regions on the west coast of Canada. Each has used a slightly different methodology and significant differences in the methods of assigning sensitivity. In order to account for the important cultural,

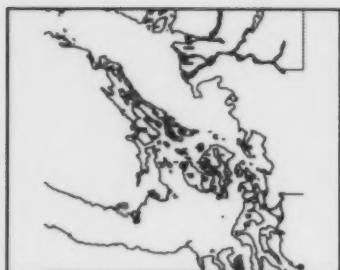


Figure 5. Spill at one hour

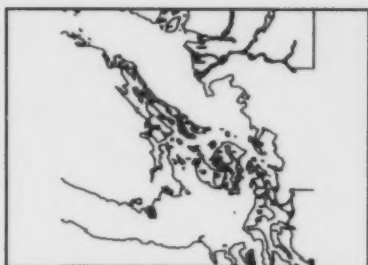


Figure 6. Spill after two hours

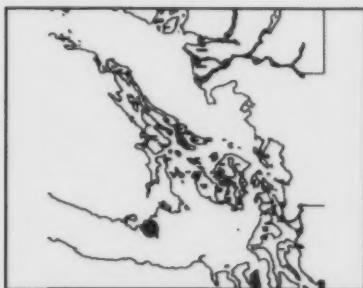


Figure 7. Spill after five hours

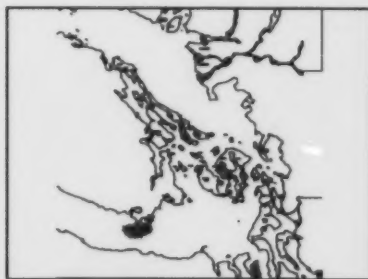


Figure 8. Spill after ten hours

biological and human resources along the B.C. shoreline, the sensitivity ranking system originally developed by Harper (Harper *et al* (1991) Harper *et al* (1992)), and subsequently refined by B. C Ministry of Environment was used to establish the environmental sensitivity maps for the area (Bones and Howes, 1991). A typical shoreline sensitivity map for Vancouver Harbour is shown in Figure 9. Similar maps for the Straits of Juan De Fuca and Puget Sound have been prepared for use in the contingency plan.

Training

Imperial Oil Limited has a network of regional response teams trained to respond to spills in their area. This local group is supported by a National Emergency Team (NET) which responds to spills anywhere in Canada. The training of all these teams involves a combination of classroom exercises

and major response simulations (McKenzie *et al* (1991)). A major simulation for PERT (Pacific Emergency Response Team) and NET based on a bitumen scenario in Vancouver Harbour was developed. The basis for the simulation was the output of the models used to develop the contingency plan and the sensitivity of the area was identified using the environmental maps developed as an integral component of the spill planning process.



Figure 9. A typical shoreline sensitivity map for Vancouver Harbour

Acknowledgements

Many people contributed to the successful completion of this project. The authors would like to thank Lok Yan for his work on integrating the orographic model into the MOSESS program. The 3-D hydrodynamic model for the West Coast was set up and run by Dr. Richard Patchen of Dynalysis of Princeton. The authors would like to thank Imperial Oil Limited for permission to publish this work. This project has been entirely funded and supported by Imperial Oil Limited.

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RECENT EXPERIENCE OF OIL SINKING

by

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Abstract

An interesting aspect of major oil spills involving fires is the extent to which the specific gravity of oil fire residues may increase to the point where sinking occurs. In one recent case reports of sunken residues from a crude oil fire were verified over large areas of the sea bed in nearshore waters. Two main causes of oil sinking were identified, namely the increased density of burnt oil residues, and secondly, the incorporation of sediment particles in the surf zone of beaches. The implications of oil sinking in this case and similar incidents are explored in the context of clean-up actions and economic impact.

Introduction

Spilt oil normally floats, but from time to time incidents occur resulting in oil sinking below the sea surface and reaching the sea bed or remaining at some intermediate level. It is in the nature of this phenomenon that verification is difficult. Oil is a highly visible pollutant and once it is out of sight it is to a large extent also out of mind. Hence it is possible that the frequency of oil sinking and the amount of material involved may have been underestimated in past oil spills. Just occasionally circumstances allow a closer examination of the fate of oil leaving the sea surface. These remarks apply equally well to the fate of dispersed oil droplets, whether as a result of natural agitation or the application of chemicals, but the paper will be largely confined to considering the ways in which oil may sink *en masse*.

Causes of oil sinking

The density of oil in relation to that of the surrounding sea water is clearly the major factor. Because of the turbulent nature of the sea and the influence of waves and currents it is possible even for slightly buoyant oil to become submerged. Perhaps the best example of this is the dispersion of oil droplets in the water column. Also larger patches of oil that become swamped in breaking seas are likely to be carried further below the surface by the orbital motion of waves and may take a long time to resurface. If the oil in question has little or no

tendency to form sheens, such as some weathered residual fuel oils, it can prove extremely difficult to track either visually or by remote sensing.

The most common cause of buoyant oil sinking is through the incorporation of solid particles. In the open sea where the concentration of suspended material is low this effect is unimportant, but in the surf zone sand grains readily become mixed into oil. The longer term fate of oil sunk in this way is likely to be burial under sediment in nearshore waters or stranding by waves casting the oil up onto the shore. In the Gulf of Suez large amounts of oil have sunk in shallow water, probably as a result of desert sand blowing onto oil spilt during oil terminal operations and from other sources.

A number of crude oils and residual fuel oils have a specific gravity greater than that of oceanic sea water (1.025 g/m^3). Notable are some of the Venezuelan crudes. Most asphalt products fall in this category and occasionally some heavy fuel oils, depending on how they are derived. Certain crudes may be buoyant in their fresh state, but will sink once their most volatile fraction has evaporated.

Given that almost all crudes and residual fuel oils contain components denser than sea water, they have the potential for sinking if the lighter components are removed. Incomplete combustion of oil creates such conditions.

The HAVEN oil spill

On 11th April, 1991 at Genoa, Italy, the M/T HAVEN suffered explosions and fire when partly laden with about 141,000 tonnes of Iranian Heavy crude. At first, the fire was fought from attending tugs, but this was soon abandoned once the fire gained strength. The fire raged during three days of calm weather after which the tanker sank in about 70 metres' depth, 1.5 kilometres off the coast. No reliable estimates exist of how much oil was consumed in the fire, but divers were soon able to report that the sunken wreck was almost completely empty of cargo. A small quantity of oil residue remained adhered to the deck and was removed with the assistance of divers during the ensuing weeks using an air-lift system.

The sea and nearby shorelines were polluted by both fresh oil and residues from the fire. The residues proved extremely persistent and some oil reached France on the westward current. Again it is impossible to be sure of how much oil was spilt, mainly because the thickness of floating residues could not be determined from aerial observation. On close examination floating patches were found to range in thickness from a few centimetres up to half a metre. Conventional methods of extrapolating

spilt oil volumes from sea surface coverage were therefore useless.

Oil also sank in significant quantities. Although the fire during 11th to 14th April was intense, combustion of the oil was not complete and the residue remaining was both more viscous and more dense than the parent oil. Judging by the distillation characteristics of Iranian Heavy crude, it is probable that once all components with boiling points of less than about 450 °C had burnt off, the residue would have a specific gravity equal to, or greater than that of sea water.

Several surveys carried out during the course of the summer of 1991 confirmed the presence of sunken oil offshore and along the coast. Sunken oil observed in the surf zone and in very shallow water is in large part likely to have been the result of incorporation of sand grains by wave action. Once sea water temperatures started to increase in June, oil globules were liberated from shallow sediments and rose to the surface. Typically, such oil was then cast ashore by surf action. Attempts were made by divers to remove oil sunk in two small yacht marinas, using improvised suction systems.

As part of the oil spill response programme, the Italian government commissioned surveys of the sea bed using remotely operated vehicles and side-scan sonar. Substantial pockets of sunken oil were found but a reliable quantitative assessment was difficult. The most successful study involved a series of 36 one-hour test trawls carried out in August and September, 1991. A commercial trawler of 18 metres, 25 tons was used with a standard trawl of 12 metres' width and fitted with otter boards. The trawls were made within about 10 kilometres of the coast and in depths ranging from 50 to 800 metres.

Oil was found in all but five of the hauls, but over 99% of the quantity was encountered in a rectangular area immediately southwest of the wreck measuring 141 square kilometres and extending from 50 to 350 metres in depth. The 16 trawls within this box swept a cumulative area of almost one square kilometre and together recovered 1,435 kg of sunken oil. The total quantity of oil available to trawls within the box can therefore be extrapolated as approximately 200 tonnes. It is possible that the distribution of sunken oil also extended further into deeper waters since the greatest accumulations were found at the seaward edge of the survey box. However, the presence of numerous old wrecks, military ordnance and other debris in this zone effectively limited the scope of the trawling.

The survey probably underestimated the total quantity of oil present since each haul is unlikely to have recovered all the sunken oil in the path of the trawl. Nevertheless the survey does provide an immediate measure of the impact of sunken oil on the commercial fishing activity

most at risk. Even small quantities of oil may spoil a whole catch and contaminate gear as well as the decks and holds of fishing boats.

General observations

It is highly improbable that the HAVEN incident is particularly unique. Viscous oil residues are a common feature of tanker spills involving major fires. In fact a similar experience was gained in connection with the grounding of M/T HONAM JADE off Yosu, South Korea on 28th February, 1983, when 2,000 tonnes of Arabian Heavy crude were lost. Some three hours after the spill, one of the clean-up contractors set fire to the main slick, which was circular in shape with a diameter of 3 kilometres. The fire burned with great intensity for about two hours before going out spontaneously and leaving a residue which sank nearby. The sunken oil affected the cultivation of crabs which were being reared in submerged cages. Some attempts were made to recover the oil using trawls, but not with much success.

It seems likely that the lack of earlier reports of sunken oil stems simply from the fact that efforts are rarely made to investigate its occurrence. The Gulf, where so many tankers were set on fire during recent conflicts, is conceivably one area where residues from oil fires may have sunk in great quantity.

The scope for recovering sunken oil is severely limited. In confined areas of sheltered water some success can be expected from using conventional dredging techniques or more improvised suction methods. In the past, marinas and harbours have been cleaned in this way after spills of, for example, asphalt. In open waters there can be no more hope of systematically recovering oil sunk over large areas than ridding the sea bed of wreckage and refuse.

OILMAP: A Global Approach to Spill Modeling

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ABSTRACT

OILMAP has recently been introduced as a sophisticated oil spill modeling tool for both spill response and contingency planning. Its structure allows it to be easily and quickly applied to any coastal or marine area. A carefully designed user interface simplifies the use of OILMAP and provides access to the many models in the system. These include a surface trajectory model, a combined weathering and trajectory model, a stochastic mode spill model, and a receptor mode model. Each of these models and the algorithms they use are described.

INTRODUCTION

OILMAP is an oil spill model system suitable for use in both rapid response mode and long range contingency planning. It was developed for a DOS-based personal computer, and employs full color graphics to enter data, set up spill scenarios and view model predictions. A convenient menu system facilitates access to each of OILMAP's main components and to features within each module. The major components of OILMAP include environmental data entry and viewing capabilities, the oil spill models, and model prediction display capabilities.

The data features include graphic routines for entering wind data, currents, and any type of geographically referenced data. Historical or forecast wind time series can be entered and revised within OILMAP. Alternately statistical wind time series can be generated from a Markov transition matrix. Both time-invariant and tidal currents can be entered for use by the models using OILMAP's current painting tool. Furthermore any type of geographically referenced data can be stored in point, line, or polygon format for future display and updating. Such data as spill response equipment, oil terminals and pipelines, spill overflights, and biological resources can be entered and later displayed on maps showing model predicted spill trajectories.

Model predictions can be displayed in conjunction with any of the data (winds, currents, shoreline, geographic) stored in OILMAP. Paper copy maps are easily made from any screen display for future reference.

Several modes of the spill model are available. The surface trajectory mode is intended for quick spill response. The weathering model includes the spreading, evaporation, entrainment, emulsification, and shoreline interaction of oil. The stochastic and receptor models simulate a large number of trajectories from a single

site for generating probability statistics. Each model is described more fully in the following sections.

SURFACE TRAJECTORY MODEL

The surface trajectory model predicts only the surface transport of oil. Oil is represented by a number of spillets of constant mass. The spillets move in response to wind and current forcing. Wind data are supplied by the user and are assumed spatially invariant. The default wind forcing is 3.5% of the wind speed in the direction of the wind. An option lets the user control both the percent of the wind speed and the angle the oil moves relative to the direction of the wind. Spatially varying background (density-induced, wind-driven, etc.) and/or tidal currents can be specified. Currents can be input by the user using OILMAP's current painting tool or can be generated by a hydrodynamic model. The oil's net motion is the vector sum of the wind and current components, plus a small random component.

The surface trajectory model operates in real time to rapidly produce estimates of a spill's movement. A relocate option enables the user to update model predictions to agree with spill observations as the simulation proceeds.

TRAJECTORY AND FATES MODEL

In addition to the capabilities of the surface trajectory model, the trajectory and fates model includes several oil weathering processes, and maintains a time dependent mass balance of the oil's fate. The weathering processes modeled are spreading, evaporation, entrainment, emulsification, and shoreline stranding. The oil mass balance is continuously updated as the simulation proceeds to give the percent of mass on the water surface, dispersed into the water column, evaporated, stranded on the shoreline, and transported beyond the model boundaries. Oil parameters such as density, viscosity, thickness, and water content are also calculated.

A maximum of 100 spillets are used to represent the oil. Each spillet is initialized with the same fraction of the total mass spilled, and then transported and weathered individually. The oil is characterized by API gravity and volume fraction by boiling point cut, viscosity, surface tension, and maximum water uptake.

Oil spreading is according to the thick slick formulation of Mackay et al. (1980). The rate of change of surface area, $A(m^2)$, with time, $t(sec)$, is:

$$\frac{dA}{dt} = K_1 A^{0.33} \left(\frac{V}{A} \right)^{1.33} \quad (1)$$

V is the spilllet volume (m^3) and K_1 is a constant with a default value of 150/sec (Mackay et al., 1980). OILMAP allows the user to vary both K_1 and the minimum slick thickness so that the spreading rate and ultimate slick size can be adjusted.

Evaporation is calculated using the boiling point cut methodology of Payne et al. (1984). This approach allows different fractions of the oil to evaporate at different rates depending on the boiling point, density and molecular weight of the cut. The mass transfer rate from each spilllet for the i^{th} constituent is:

$$\frac{dm_i}{dt} = \frac{K_2 P_i A f_i M_i}{RT} \quad (2)$$

where P_i = vapor pressure (atm), A = spilllet area (m^2), f_i = fraction of spilllet which is constituent i , M_i = molecular weight (g/mol), R = gas constant (8.206×10^{-5} atm $\cdot$ m^3 /mol $\cdot$ K), and T = temperature (K). K_2 is the mass transfer coefficient given by Mackay and Matsugu (1973) as:

$$K_2 = 0.029 W^{0.79} D^{-0.11} S_c^{-0.67} \sqrt{\frac{(M_i + 29)}{M_i}} \quad (3)$$

here W = wind speed (m/hr), D = spilllet diameter (m) and S_c = Schmidt number. Following Mackay et al. (1980), the Schmidt number for cumene, 2.7, is used. The molecular weight term in Eq.(3) is a correction for diffusion in air (Payne et al., 1984).

The entrainment of oil from the sea surface into the water column is calculated using the methodology of Delvigne and Sweeney (1988). The entrainment rate is expressed as:

$$Q_d = C^* D_d^{0.57} S F d^{0.7} \Delta d \quad (4)$$

where Q_d = entrainment rate of oil droplets, with droplet sizes in an interval Δd around d_0 , per unit surface area (kg/m^2 sec)

C^* = empirical entrainment constant which depends on oil type and weathered state

D_d = dissipated breaking wave energy per unit surface area (J/m^2)

S = fraction of sea surface covered by oil ($0 < S < 1$)

F = fraction of sea surface hit by breaking waves (white caps) per unit time (sec^{-1})

d = oil particle diameter (m). The oil droplet size range typically varies from 2-1600 μm with most of the oil volume in the 50-300 μm droplet size range.

Δd = oil particle diameter interval (m)

The dissipated wave energy is given in terms of the breaking wave height by the expression

$$D_d = 3.4 \times 10^{-3} \rho_w g H_b^2 \approx 34.0 H_b^2 \quad (5)$$

where

- ρ_w = density of seawater (1025 kg/m³)
 g = gravitational constant
 H_b = breaking wave height (rms value)

The fraction of sea surface hit by breaking waves is parameterized as

$$F = 0.032 \frac{(W - W_T)}{T_w} \quad (6)$$

where

- W = wind speed at 10 m above the sea surface (m/sec)
 W_T = wind threshold for breaking waves to be initiated (~5 m/sec)
 T_w = significant breaking wave period (sec)

If the wind speed is less than the threshold value, $F = 0$ and no oil is entrained.

Based on observations breaking wave events rapidly distribute the oil in the near sea surface zone typically restricted to a depth

$$z_m = (1.5 \pm 0.35) H_b \quad (7)$$

the entrainment rate given in Eq. (4) is for one size class $d_0 - \Delta d/2$ to $d_0 + \Delta d/2$. To obtain the total entrainment rate Eq. (4) is integrated over all particle sizes extending from the minimum to maximum size classes.

Emulsification, or mousse formation, is modeled using the algorithm of Mackay et al. (1980, 1982). The rate of water incorporation into a spilllet is characterized by:

$$\frac{dF_{wc}}{dt} = C_1 (1 + W)^2 (1 - F_{wc} / C_2) \quad (8)$$

where

- F_{wc} = fraction of water in oil
 W = wind speed (m/s)
 C_1 = water incorporation rate constant $\sim 2 \times 10^{-6}$ for emulsifying oils
 C_2 = oil dependent constant, 0.7 for crude oils and heavy fuel oil, 0.25 for home heating oil

The increase in oil viscosity due to water incorporation is calculated according to Mooney (1951) as:

$$\mu = \mu_o \exp \left(\frac{2.5 F_{wc}}{1 - C_3 F_{wc}} \right) \quad (9)$$

where

μ_o = parent oil viscosity

C_3 = mousse viscosity constant, ~ 0.65

The effect of evaporation on viscosity is calculated following Mackay et al. (1980, 1982) as

$$\mu = \mu_o \exp (C_4 F_{evap}) \quad (10)$$

where

C_4 = oil dependent constant; 1 for gasoline, light diesel; 10 for crude oils

F_{evap} = fraction of oil evaporated

Equations (8), (9) and (10) are used to simulate mousse formation and the resulting increase in oil viscosity.

For oil transported onshore, the amount of oil actually deposited depends on the type of shoreline and oil viscosity, following the work of Reed et al. (1989). Once the shoreline's oil holding capacity is reached, spilllets are no longer deposited in that coastal cell. Instead, the oil is kept offshore where it is transported along the coast by winds and currents, until a coastal cell that is not oil saturated is reached. OILMAP defaults all shorelines to sand if shoreline types are not specified.

STOCHASTIC MODEL

The stochastic model executes a user-specified number of simulations from a single source varying only the environmental conditions at the time of the spill. The spill release occurs at random times over a given month or over the entire year. Historical wind records may be used, or the model can generate wind time series from zero- or first-order statistical distributions. The weathering processes included in the trajectory and fates model are included in the stochastic model. Final output of the stochastic model is a probability grid showing the direction oil will move from the site and where it will impact land. This mode of OILMAP is particularly useful for contingency planning since it allows the oil's most probable direction of transport to be identified and delineates the relative risk to different coastal areas.

RECEPTOR MODEL

The receptor model works much like the stochastic model, only in reverse. A large number of simulations are run from a single receptor site varying the

environmental conditions for each scenario. Historical or statistical winds may be used. Oil fates are not included. Simulations are run backwards in time to identify the probable directions from which oil will approach the receptor site. Final outputs of the receptor model are gridded probabilities of the oil's approach direction and time contours showing the minimum time for oil to reach the receptor site. These data are useful in contingency planning for establishing the vulnerability of critical resources to oiling, and estimating the time available to implement response strategies in relation to the oil's position.

CONCLUSION

OILMAP is a comprehensive oil spill model system that is suitable for worldwide application. Its clever user interface simplifies access to its many features making rapid spill response possible even for novice users. The spill models within OILMAP utilize algorithms which have been shown to give reasonable approximations of the processes they describe. OILMAP's utility has been provided through application to actual spill event (Spaulding et al., 1992) in which model predictions were available within half an hour of notification of the spill.

Several additional capabilities are planned for OILMAP. Nearing completion are modules to simulate tactical spill response (cleanup operations), search and rescue operations, and oil impacts on sensitive resources. Other components planned over the next year include subsurface oil transport, a chemical spill model, and impact assessment models.

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PC-BASED VISUALIZATION OF GEOGRAPHICALLY REFERENCED ENVIRONMENTAL DATA

by

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Abstract

Geographical Information Systems (GIS) technology provides sophisticated data handling tools for use in oil spill response and contingency planning, yet many PC-based GIS systems, although powerful, have an inadequate user interface, poor presentation capabilities, and require extensive training to operate. ASAMAP is software that employs a state of the art graphical user interface to collect and display geographically referenced data on an MS-DOS platform. The program is easy to learn and simple to operate, facilitating data collection and visualization in an inexpensive decision support system suitable for oil spill response or any application requiring spatial data handling. The software operates on a PC-compatible laptop computer and is mouse-driven, using "buttons" and screen icons to interactively manipulate data on colorful maps on the screen. During response to an oil spill, ASAMAP provides enhanced data capture and visualization, facilitating faster assimilation of information and a more efficient decision making process.

Introduction

Geographical Information Systems (GIS) are tools for scientists, engineers, and planners involved in oil spill response and contingency planning that have become widely available through inexpensive PC hardware and software. GIS software combines automated mapping functions with database management capabilities, linking data to places upon and beneath the surface of the earth. This linkage allows one to query and manipulate a database using spatial selection techniques. As an example, a GIS user might define a segment of coastline within a wildlife refuge (the spatial selection) and extract from the database information on shore type and the amount of oil within each shore type observed and measured after a major offshore spill. The extracted data could then be overlain with data describing the wave and current regime along each shoreline segment, and the result incorporated into a model which could then predict the fate of the oil. The results of the model could then be used by scientists to devise cleanup strategies and by managers to allocate cleanup resources.

The ability to manipulate data in this fashion is the promise of GIS technology and the desire of many workers in the environmental field who need to interpret large quantities of geographically referenced data. The reality of GIS is that the complexity of data manipulation within GIS software frequently requires significant effort and time from the user. In general, the level of effort is proportional to the sophistication of the desired spatial operation. This difficulty has created an obstacle to most users of spatially referenced environmental data and made them reliant on specialized GIS analysts. In order to provide a useful tool for data visualization to a larger group of individuals, at least two approaches seem appropriate. The first approach would be to add simple data viewing, query, and display capabilities to existing complex GIS software for the PC. Presently, PC-based GIS software capable of complex spatial operations generally have poor user interfaces, cumbersome data display capabilities, and require lengthy training to operate. The second option is the development of software that provides a graphical and intuitive interface to spatial data sets. These programs could provide access to multiple data formats, run on low-cost PC platforms, be simple to learn and easy to use.

This paper describes ASAMAP, software developed by Applied Science Associates to meet the need for extending access to geographically referenced data to a larger group of scientists, engineers, and managers in all fields. The utility of the ASAMAP program is discussed within the context of Geographical Information Systems software currently available for the PC, and ASAMAP's capabilities for oil spill response and contingency planning in the marine environment are summarized.

The GIS Data Model

Geographical Information Systems are a relatively new technology that has grown rapidly over the past few years (ESRI, 1990). There are many definitions of GIS as well as some dispute over what the technology should encompass. For the purposes of this discussion the following definition from Burrough (1986) will be used: GIS is "a powerful set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world for a particular set of purposes". Or stated more simply, GIS is "a computer system that can hold and use data describing places on the earth's surface" (Rhind, 1989). These data describe real-world objects relative to a coordinate system, the attributes that characterize the objects, and the spatial relationships between objects. GIS technology can also be thought of as a means to manipulate data representing a model of a natural system in the real world. The ease with which this data can be manipulated will dictate how well the modeled system is understood.

Computer technology now allows researchers to gather extraordinarily large data sets, and there is increased demand for GIS tools to organize and interpret these data. One goal for any individual working with large data sets is to assemble the data for maximum usability. Data structure should be such that access is simple and direct, and interpretation is enhanced. The method of data retrieval and query should be non-obtrusive, interactive, and simple to master. The graphic display of data should be dynamic, colorful, and interactive. Unfortunately, these adjectives

do not accurately describe much of the GIS software presently available for personal computers.

Present GIS software for the PC provides powerful, low-cost tools for spatial data manipulation in a few general formats and with widely varying levels of graphical interaction. The more flexible and usually more powerful systems work as a collection of functions sometimes referred to as the "tool box" approach. The user must learn the specific uses of each of the functions or "tools", and assemble them into macros to manipulate the data. Through macro development, these systems can be customized to perform virtually any GIS task, yet the learning curve is often long and the user interface inadequate. A second format for PC GIS takes advantage of current Graphical User Interface (GUT) technology to achieve ease of use and better data display capabilities. These systems are easier to use but sacrifice flexibility and the possibility for customization and complex macro authoring found in the tool box approach. For specific applications requiring little modification, these systems are inexpensive solutions to GIS needs. The third approach involves linking Computer-Aided Design (CAD) with relational database software to form a GIS. These systems combine the strong graphics precision inherent in CAD programs with the data query capabilities of relational data bases. They however are frequently slow and difficult to learn to operate. If the desired GIS capability is one incorporating powerful spatial overlay capabilities, ease of customization, and a intuitive graphical interface to spatial data sets, then one must look to other software to use as an interface to geographic data.

Data Access Through a Graphical Interface

ASAMAP uses a state of the art graphical interface to provide easy access to any kind of geographically referenced data. All commands can be accessed using the mouse to select buttons on the screen, and the interface utilizes moveable, scaleable windows to present choices and information to the user (Figure 1). The software operates on an IBM PC or compatible with at least a 20 megabyte hard disk drive, 640 kilobytes of RAM, VGA color graphics card and monitor, a math co-processor, and a mouse. Map and attribute data are imported into the program in ASCII text files, or entered interactively using the mouse and keyboard, and stored as vectors in a database. Each database consists of 50 layers and the number of databases is limited only by hard disk space. Each layer can be assigned a meaningful name by the user and turned on or off to overlay different information in the data window, thereby assembling a customized view of the data. Once the desired view is created it can be sent to a printer or saved as a graphics file in PCX format for use with other software. The user may easily move from one database to another and from one geographic area to another by selecting buttons with the mouse. Other operations performed on layers include turning layers on and off, deleting layers, exporting and importing layers between databases, and copying layers.

Once the map data are assembled into databases and layers, attribute data in the form of graphics or text files describing the mapped objects may be linked to individual objects. Text link files may be created using simple text editors, and graphics (including scanned images) may be created using software capable of



Figure 1. Example screen images from ASAMAP software. Top view shows the map window and screen menu buttons. Bottom view illustrates access to commands within sub-menus using screen buttons.

producing PCX format files. Any text or image linked to a map object may then be viewed by selecting the object with the mouse. In addition, any data that can be stored in gridded form (i.e. the x-y-z triplets of topography) may be viewed and overlain by vector or text information. Gridded data sets of topography and bathymetry are readily available on CD ROM and easily accessed and displayed in ASAMAP.

Applications to Oil Spill Response and Contingency Planning

The precursor to the graphical user interface utilized in ASAMAP was developed for an oil spill contingency plan for Prince William Sound after the Exxon Valdez spill in the Spring of 1989. The Alyeska Tactical Oil Spill Model (ATOM) was developed by Applied Science Associates as a PC-based decision support system for spill managers (Anderson, et al., 1990). ATOM software integrated oil spill response management techniques, oil fates and trajectory modeling, oil cleanup technology, and biological impacts assessment methodology within a unique graphical interface. ASAMAP grew out of this numerical modeling environment into a visualization tool that may be applied to any application, but is particularly well suited for oil spill response.

During oil spill response, geographically referenced data are collected almost continually, and the individuals directing the response require uncomplicated and direct access to the data for rapid assimilation. Following the spill and cleanup of 288,000 gallons of fuel oil from the World Prodigy tanker at the mouth of Narragansett Bay on June 23, 1989, August, et al. (1990) analyzed the effectiveness of GIS tools used during the response and damage assessment processes. They identified the primary uses for GIS during spill response and cleanup and gave recommendations for better utilization of GIS technology in future spill response efforts. Their assessment points out some of the shortcomings of GIS software for use within the compressed time of an oil spill. Data entry was identified in the study (August, et al., 1990) as consuming a large amount of time during the early phases of the spill. As an example, all overflight maps depicting the extent of the oil slick and the segments of oiled shoreline had to be taken to a separate GIS facility located away from the response command center and digitized. This slowed the data collection, redistribution and assimilation process. A second use of the GIS cited in the August, et al. (1990) study was the daily plotting of maps of the spill extent for use in deciding which shellfishing and swimming areas to reopen, and for daily presentations of the collected data to the press. This required the additional step of formatting the data for hard copy output and printing the required number of maps for distribution.

Because ASAMAP is highly portable and runs on small laptop computers, it is well suited for quick set up in remote sites and in the field. Data brought to a spill command center can be quickly entered through a digitizing tablet or entered directly with the mouse. Use of the software requires little training and operation is straight forward and intuitive. The data visualization capabilities within the software make it ideal for presentations of mapped information. Through the use of relatively simple overhead projection equipment, the image on the computer screen can be displayed to large audiences involved in the spill response and to members

of the press. The software has been used successfully for presentations of complex data to non-technical audiences and eliminates the need for paper maps.

Based on the World Prodigy experience, August, et al. (1990) recommended that to enhance the use of GIS technology during future oil spills, a GIS should be configured for spill response prior to the spill event. Part of this configuration would include a baseline data set so that time is not wasted during the spill capturing coastlines, transportation networks, political boundaries, biological habitats, land cover classifications, and shoreline sensitivity data. With baseline data in place within ASAMAP software, respondents to a spill can work quickly to build and update the data base, and make presentations of the information in a simple, effective way.

Future Developments

ASAMAP software is well suited to oil spill response and contingency planning, but it can also provide a window through which any type of geographically referenced information can be viewed. The dynamic user interface developed within ASAMAP is suitable for integration with all types of numeric models. The interface is currently being used with oil spill and water quality models developed for the PC (Spaulding, et al., 1992; Swanson, et al., 1992), and a near-shore wave model is currently being implemented in the same format. The animation of oil spills within the proper geographic context is a powerful tool and enables one to assess the impact of the spill on the mapped resources stored in the geographic database and displayed interactively. Another new application currently being developed is a real-time link to a Global Positioning System (GPS) which will allow the user to receive, process, and display the position of a GPS transmitter on a base map on the PC screen. One potential use of this integration is for tracking oil spills using drifters equipped with GPS transmitters as discussed by Lange (1990).

Conclusions

GIS software for the PC has evolved rapidly in recent years, yet the most powerful systems still lack an intuitive graphical user interface, have poor data display capabilities, and require specialized training to use effectively. For those wishing to manipulate spatial data efficiently, one approach is to combine a powerful GIS operated by a GIS analyst with an inexpensive and easy to use system incorporating all the advantages of a graphical user interface. This approach fulfills the need for complex spatial analysis and provides a larger number of individuals access to the data for interpretation and display. It removes many of the obstacles encountered in transforming data into useful information through simple and effective visualization techniques.

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ADIOS-Automated Data Inquiry for Oil Spills

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ABSTRACT

The authors and colleagues have developed an intelligent computer database which has properties stored for several hundred oils and oil products combined with a model for oil weathering. Environmental data is input by the user through a menu-driven graphic interface. The format of the output is designed to provide immediate information relevant for clean-up decisions. Typical output information include changes in key physical parameters (density, viscosity, water content of emulsions) over time and an oil loss budget at any specific time.

INTRODUCTION

Traditionally, when a spill occurs, information on the oil or oil product is supplied by the spiller or extracted from printed databases. The behavior of the oil is then estimated by using traditional rules-of-thumb or a more sophisticated computer-based weathering model, often requiring ad hoc modification of the data to fit the input format expected by the model. Both methods require knowledge or tools which may not be available at the scene of the incident. The authors and colleagues have developed an intelligent computer database which contains properties for several hundred oils and oil products combined with a model for oil weathering. The resulting software

package is designed to provide spill response decision makers with a first guess at the fate of the oil or product due to natural weathering processes.

DATABASE

Several existing databases were used to provide information to ADIOS. The most directly applicable one for spill simulation was developed for Environmental Canada (Bobra and Callaghan, 1990). It lists properties, divided into 18 categories, for more than 100 oils or oil products. Most of the properties are the results of direct measurements and define intrinsic characteristics of the material (e.g. density, viscosity, interfacial tension), while others provide coefficients for formulas or parameters from laboratory trials which are designed to indicate behavior in actual spill circumstances (e.g. weathering, dispersibility).

As useful as this database is for responders, it has some definite limitations. First, it is not a spill behavior model. While several properties of the oil or product are tabulated for different stages of weathering, there is no way to directly tie these changes to each other or to the weathering formula. Second, the information on any individual oil is often incomplete or assembled from different sources with no attempt to reconcile discrepancies. For example, the pour point for fresh Statfjord crude oil is listed as either -15 °C or 4 °C, depending on the research study utilized. This is not the fault of the database so much as it is the uncertain nature of many of the properties, such as pour point, often used to describe crude oil.

A very extensive description of oil fields is provided by the U.S. Dept. of Energy either in electronic or hard copy form (BPO, 1987). The format of this information is designed for refinery operations, but at least one

weathering model has been constructed to accept the data as input to its algorithms (Payne et al., 1984). One handicap of this database as an information source for spills is that it does not include blends of oils. Such blends are often shipped and present a risk for spillage.

The Oil Companies European Organization for Environmental and Health Protection, CONCAWE, has assembled a list of 57 crude oils, mostly from the Middle East or Europe, and grouped them by pour point and expected evaporative loss. The information is similar to the information assembled for Environmental Canada. The authors have also received some crude oil data directly from the oil companies. This information is usually in the same format as the Department of Energy database.

Refined products present their own challenges since there are often ambiguities in the naming conventions used. For example, the Canadian reference, The Basics of Oil Spill Cleanup(1978), lists naptha as any of various volatile hydrocarbon mixtures used chiefly as solvents and diluents. This obviously covers a wide variety of petroleum products. Terminology for the same material differs from region to region and individual formulations reflect the nature of the original crude oil and the specific commercial application for the product. NOAA has produced a reasonably generic handbook of chemical and physical properties for such constituents (Curl, 1977) and the authors have contacted the major oil companies for descriptions of the particular refined products which they make.

ALGORITHMS

ADIOS models changes in three oil properties and four physical processes acting on the oil. The three properties are density, viscosity, and water content.

Fay as 1.14 and 1.45 respectively. The other terms are defined as

V_o = volume of oil spilled (m^3)

ν_w = dynamic water viscosity ($kg/m \text{ sec}$)

ρ_w = water density (kg/m^3)

ρ = oil density (kg/m^3)

Fay's original formulas neglected the spread and horizontal transport of the oil due to winds, currents and waves. Including in ADIOS all the parameters that affect the slick would require, among other things, specific geographic details and the tracking of individual patches as the spill broke up into distinct pieces. This would necessitate a large impractical increase in required input data. As an alternative, Fay's formula is modified to incorporate the increased spread rate of the slick along the axis of the wind. This results in an elliptical spread with the rate of area change given by

$$\frac{dA}{dt} = \frac{d}{dt}(\pi R(R + c_w w t))$$

where R is the radius of the slick that would be expected for regular Fay gravity-viscous spreading, w is the wind speed, and t is the time after release of the oil. The constant c_w is empirically determined.

The rate of change of R is adjusted to incorporate any new oil discharged and any loss of oil due to evaporation. (The effect of dispersion into the water column on spread rate is ignored as these two processes usually operate on different time scales.)

The two major processes which remove oil from a slick are evaporation and oil-in-water dispersion. An algorithm developed by Stiver and Mackay (Stiver,

The four physical processes are spreading, evaporation, oil-in-water dispersion, and water-in-oil emulsion formation. Various alternative algorithms exist to describe the same process. The criteria that the authors used to select any particular algorithm were: (1) agreement with empirical data, (2) theoretical rigor in its derivation, and/or (3) acceptance as an industry standard.

The use by ADIOS of the Fay formulas (Fay,1971) to describe spreading is an example of this last criterion. While by far the most widely adopted equations to describe spreading, the formulas do not describe the shape and generally underestimate the area of experimental oil spills (Jeffery,1973; Cormack,1978; Lehr,84). In order to ameliorate these problems, the authors modified the standard approach to Fay spreading. The modification uses Fay's standard gravity-inertial processes during the early part of the spill but uses a more general expression that incorporates wind effects for the gravity-viscous spreading formula. Fay's surface tension spread is not used in the model since this spreading (thickness of the oil in this stage is around 0.01 mm.) occurs over time frames and sea-state conditions which are not typical for the spill scenarios modeled by ADIOS. The gravity-inertial phase, which lasts on the order of five minutes for most spills is taken by ADIOS as defining the initial area for the longer lasting gravity-viscous phase. The area at the transition, A_0 is given by

$$2) \quad A_0 = \pi \frac{k_2^4}{k_1^2} \left(\frac{V_0^5 g \frac{\rho_w - \rho}{\rho_w}}{v_w^2} \right)^{\frac{1}{6}} \quad (m^2)$$

where k_1 and k_2 are empirical constants defined by

1984) is used to compute evaporation rates:

$$\frac{df}{d\Theta} = \exp\left[6.3 - \frac{10.3}{T}(T_0 + T_G f)\right]$$

Here, f is the volume fraction of oil evaporated, T is the temperature of the oil, T_0 and T_G are oil-dependent parameters derived from the fractional distillation data. The evaporative exposure is a dimensionless variable related to time:

$$\Theta = \frac{K_m A t}{V_0}$$

where the mass transfer coefficient, K_m , is a function of wind speed and the length of the slick in the downwind direction. Since many oils emulsify rapidly, an adjustment was made to account for the decrease in the evaporation rate as the water content increases. The mass transport coefficient is scaled linearly with the oil fraction in the emulsion.

Vertical dispersion of oil is estimated using a slight modification of a model developed by Delvigne et al. (1987) and Delvigne and Sweeney (1988), who measured the number and size distribution of oil droplets which are driven into the water column by breaking waves, whose presence is signaled by the presence of whitecaps. The vertical entrainment of oil is directly proportional to the dissipation of energy of a single breaking wave, the total dissipation rate for given wave spectrum, and the volume of oil injected into the surface layer each time a wave breaks.

The dissipation of wave energy per unit surface area is given by (Delvigne and Sweeney, 1988)

$$D_e = 0.0034 \rho_w g H_{rms}^2$$

where

D = dissipated wave energy per unit area (J/m^2)

H_{rms} = root-mean-square wave height (m)

Since H_{rms} is a quadratic function of wind speed, the value of D can be very sensitive to changes in wind strength. Delvigne and Sweeney (1988) assume that the fraction f_w of sea surface covered by whitecaps can be calculated, and that the vertical entrainment of oil is directly proportional to the fraction of waves that break per wave period f_{bw} , estimated to be

$$f_{bw} = \frac{f_w}{t_p}$$

where t_p is the peak wave period. Delvigne and Sweeney take f_w to be a linear function of wind speed with the familiar cutoff value of about 5 m/sec, below which whitecaps and oil entrainment cease. Recent studies of whitecap coverage by O' Muircheartaigh and Monahan (1986), Wu (1986), and others have prompted the authors to use a more general power law of the form

$$f_w = r \cdot w^s$$

where $r = 3.0 \times 10^{-6}$ and $s = 3.5$ (Monahan and O' Muircheartaigh, 1980). This power law produces relatively larger entrainment rates at high wind speeds than the linear regression form. Also, it allows for non-zero entrainment at moderately low wind speeds, which is consistent with field observations.

Droplet size distributions were measured in a series

of experiments conducted in 15- and 200-meter long wave tanks, respectively and in a large vertical tank in which the oil was injected at depth. Fresh crude Ekofisk and Prudhoe Bay oils were used. Experiments were also conducted on 3-day and 10-day old Prudhoe Bay oil. Aside from oil-specific constants, the "steady state" size distribution of oil droplets remaining in suspension after the passage of a single breaking wave, was the same, regardless of the oil type, age or experimental conditions. The following "universal" droplet spectrum is used in the present model:

$$N(d) = N_0 \left(\frac{d}{d_0} \right)^{-2.3}$$

where $N(d)$ is the number of oil droplets per unit volume of water per unit droplet diameter, and N_0 and d_0 are reference values.

The volume of oil V per unit volume of water is obtained (to within a constant) by integrating the product of the droplet volume and the frequency distribution of droplets over the volume of oil. In practice, the integration is performed between the minimum droplet size, $d_{\min}$, and maximum droplet size, $d_{\max}$, determined from the experimental data. This yields

$$V \propto \frac{1}{1.7} [d_{\max}^{1.7} - d_{\min}^{1.7}]$$

Since the larger droplets re-surface due to buoyancy, $d_{\max}$ is obviously a function of time after the wave breaks, until the remaining droplets are small enough to be held in suspension. A value of $d_{\max} = 60 \mu\text{m}$ has been chosen by eyeballing the "steady-state" tail of

the droplet diameter vs time curve given by Delvigne et al. (1987), Figure V.20, and Daling et al. (1990), Figure 5. The value of $d_{\min}$ is taken to be 5 μm , which is a reasonable figure since the use of $d_{\min} = 0$ introduces negligible error compared to that found in any of the other terms.

The reverse of oil being driven into the water is water being incorporated into the oil to form a water-in-oil emulsion. Many oils form long-lived emulsions called "chocolate mousse". Some careful experimental studies by Bobra (1990) show a correlation between the asphaltenes in oil and an oil's propensity toward forming a mousse. However, the rates at which emulsions form and the mechanism by which mousse is stabilized have not been characterized sufficiently to reliably model the process quantitatively. ADIOS incorporates a very simple first order rate law for mousse formation first proposed by Mackay et al. (1980):

$$\frac{dY}{dt} = k(1 - \frac{Y}{Y_f})$$

where Y is the volume fraction of water in the emulsion, Y_f is the asymptotic value for the water fraction, and the rate at which mousse is formed, k , is a function of sea state and the composition of the oil. This rate constant can be adjusted using experimental data or field observations.

Emulsification and evaporation produce changes in the physical properties of the oil. The two properties followed by ADIOS are density and viscosity, since both have a direct bearing on the appropriate clean-up procedures for any spill. The change in density due to evaporation is assumed to be linearly related to the fraction evaporated as hypothesized in the model of Mackay et al. (1983). A similar linear adjustment is

done to correct for density change due to differences between the ambient temperature and the reference temperature used for computing density in the database. Finally, the density of the water-oil mixture, if emulsification has occurred, is calculated by doing a weighted average of the two densities. Thus the reported density is

$$\rho_m = Y\rho_w + (1 - Y)\rho_o(1 - c_1(T - T_o))(1 + c_2f)$$

where ρ_m is the mixture density, ρ_o is the reference density and T_o is the reference temperature. The constants c_1 and c_2 are empirically determined.

A similar equation holds for the computation of viscosity. The increase in viscosity as a function of water content of the emulsion is correlated using the Mooney equation (Mackay, 1979). The adjustments for temperature variation and evaporation are described by exponential functions (Mackay and Stiver, 1983). The reported viscosity is then computed as

$$v_m = v_o \exp\left(\frac{c_3}{1 - c_4 Y}\right) \exp\left(c_5 \left[\frac{1}{T} - \frac{1}{T_o}\right]\right) \exp(c_6 f)$$

The constants c_3 through c_6 have to be empirically determined.

INTERFACE AND SYSTEM STRUCTURE

While currently available only in a stand-alone form, ADIOS will eventually be part of a larger spill model which includes oil transport. Therefore, it is designed to keep track of different segments of the oil and weather and adjust their physical properties independent of the remaining segments. For the stand-

alone model, these segments are distinguished by their release time. In the larger model, they may have spatial variations as well. The major exceptions to this process are the spreading rules which work on the whole spill since spread rate is not a linear function of the spill volume. The evaporative mass transfer coefficient is also a function of the whole spill.

In order to allow easy future modification of the software, the computational engine of ADIOS, containing the weathering algorithms, is isolated from the input, oil database, or output screens. Pre-processor modules collect or send information from or to these areas, verify its completeness and reasonableness, and prepare it for access by the computational engine. This process is, of course, not apparent to the user who interacts with ADIOS through various graphical interfaces (see Figures 1 and 2). For example, the user selects the oil or product from a scrollable list and ADIOS then loads all the

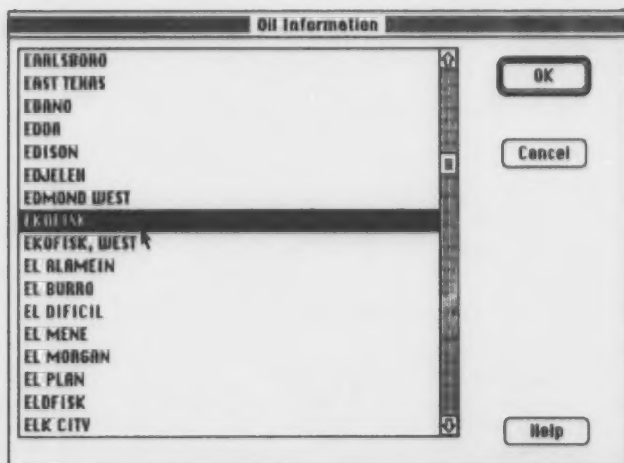


Figure 1

property values (or default values if the property values are not known) necessary to run the computational engine.

Similarly, environmental data consisting of wind, wave and temperature information is entered graphically. Currently, ADIOS limits the data to one week, since this is the limit of reliability for wind data. Only spatially uniform wind are permitted. The duration of the wind time step is selected by the user. Source data on spills is often highly unreliable and extremely sketchy. Therefore, the authors thought it was not useful to include complicated routines to estimate spill release. Two options are provided to the user. Either the oil may be released all at once or at a steady rate over a fixed period of time. No spatial variations in source release, such as a leak from a moving tanker, is handled because transport is not modeled in the stand-alone version. While such

Enter the Amount of Oil Spilled

Enter the duration of the spill Help

☐ The spill is instantaneous

☒ The spill is continuous for hours

Enter rate or total amount spilled Help

☒ The spill rate is bbbls/hr

☐ The total amount spilled is bbl

OK Cancel Help

Figure 2

options will be available when ADIOS is coupled with a pollution transport model, the tradeoff will be a large increase in the amount of input data required and the expertise needed by the user.

Output that is difficult to interpret is not useful in emergency situations like oil spills. ADIOS presents the results of its calculations either as pie charts or graphs. The pie charts are used to show a snapshot at a given time of the mass balance of the spill (fractions evaporated, dispersed and remaining). The graphs trace the evolution over time of a particular property of the oil, for example viscosity versus time. Whenever appropriate, reference markers useful for cleanup are indicated, for example a mark at the point where the oil becomes too viscous for normal dispersant application.

CONCLUSION

While subject to all the limitations inherent in such models, the stand-alone version of ADIOS should provide a useful tool to spill responders to help them to estimate the extent of their pollution problem and the time frame for particular cleanup techniques. It is not a replacement for on-scene measurements and observations and will have to be coupled with a transport model to provide a complete prediction of the fate of the spill.

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THE EVAPORATION OF HEAVY OIL STRANDED ON SHORELINES

by

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ABSTRACT

Laboratory experiments have been conducted to measure the evaporation rate of a medium gravity-like crude oil made up of a bitumen / condensate mix, on various wet shore materials as substrates. The data is required for contingency planning on the Canadian west coast through which this hydrocarbon is exported. The experiments were conducted on shore material obtained from Georgia Strait with a bitumen / condensate mix that had been previously weathered for 24 hours to simulate oil which had been on the water for a short time before being beached. The experiments appear to show that shore materials with high surface areas (such as mixes of large rocks and shell fragments) lose oil to evaporation more readily than well sorted sands.

INTRODUCTION

Contingency plans for accidental oil spills are intended to provide the spill responder with the best available information on the situation he is likely to encounter. A contingency plan recently generated for the shipment of heavy oil through the Port of Vancouver includes predicted oil spill trajectories based on a stochastic computer model developed by Imperial Oil (Goodman et al.(1992)). One aspect of the model is a prediction of the amount of oil which might have to be removed from impacted shorelines. Laboratory measurements of shoreline evaporation were undertaken to provide the computer model with realistic evaporation rates so that good estimates could be made of the likely amounts of oil to be found as a function of time after the spill. Laboratory measurements to determine the evaporation rates were necessary because of the unusual nature of the heavy oil being modelled. The bitumen / diluent mix (known as Dilbit) is transported by pipeline from northeastern Alberta to the Port of Vancouver. Here it is loaded onto tankers for export to the far east through the Straits of Georgia and Juan de Fuca. In the unlikely event of a spill, one would expect the light diluent component, a gas condensate, to evaporate very quickly. This would result in a spilled material whose chemical and physical properties would probably change very rapidly and ultimately become those of bitumen (Brown et al.(1991)). In computer spill simulations made for this contingency plan, spilled oil might be expected to wash ashore about one day after an incident. Hence for these studies the Dilbit was weathered for 24 hours before the evaporation experiments.

EXPERIMENTAL METHOD

Shoreline evaporation was measured on model shores in the laboratory by determining the weight loss of spilled weathered Dilbit as a function of time. The model shorelines for the evaporation experiments were constructed from shore material obtained from several sites on Vancouver Island and the Gulf Islands. The locations from which the material was obtained and a description of the shore types are as follows.

Sample 1 - Obtained from Drew Harbour on Quadra Island, B.C. This sample from Rebecca Spit represents a generally sheltered location subjected to occasional storms at the north end of Georgia Strait. Samples were taken from the top 3" of shore at the mid tide point. This sample is predominantly poorly sorted sand and shell fragments with 30% rocks of all sizes up to 4 cm. The shoreline would correspond to the low energy mixed sediment beach described in Dickins et al.(1990). It is rich in fauna containing whole clams, barnacles, and small crabs.

Sample 2 - Obtained from the Sutil Channel side of Rebecca Spit, Quadra Island, B.C. This location is an active shore subject to the storms and high tide ranges of Georgia Strait. The sample consists of well rounded rocks varying in size from 10 cm to less than 5 mm with a very small amount of sand. Small shell fragments constitute about 10% of the material. This shoreline would correspond to the high energy mixed sediment beach of Dickins.

Sample 3 - Sample 3 is from a well sorted sandy shore at Saratoga Beach near Campbell River on the east coast of Vancouver Island. This shore is a tidal flat of low wave energy on the north end of Georgia Strait and is described in Dickins as a sand sediment beach. The sample is very clean with no rocks or shell fragments.

Sample 4 - Obtained from Oyster Bay near Campbell River, B.C. This sample of fine sediment and sand came from sand bars in low energy estuary of the Oyster River. It appears generally darker than Sample 3 with some strands of brown material mixed into the other sand.

The experiments were conducted by placing dried samples of one of the shore material types into aluminum trays 30 cm by 30 cm in area and 5 cm deep. The material was supported about 5 mm above the bottom of the trays with Tyler mesh size # 60 stainless steel screens set on spacer bars. Several drainage holes, which could be plugged, were drilled in the tray bottoms. At the beginning of each experiment, a mass of shoreline material varying from approximately 2 kg to 3.5 kg depending on the type, was placed in each of two trays. This provided a shore material depth of about 10 times the thickness of oil to be spread on the shore surface. The trays were then flooded with sufficient water to cover all the shore material except large rocks or shells. Approximately 100 ml of weathered Dilbit (sufficient to cover the shore surface to a depth of 1 mm) was poured onto the water surface and allowed to spread

for 10 minutes to obtain a uniform covering of the tray. Bitumen was similarly spread onto the water surface of the second tray. The holes in the tray bottoms were then unplugged and the water allowed to drain out slowly. This action would model the stranding of an oil slick at high tide under low wave activity. Oil was left uniformly covering the shore material. When the trays had stopped draining (after about 5 minutes), they were placed on balances in a controlled temperature room and the weight losses due to evaporation from the Dilbit and Bitumen covered shores were measured over a four day period.

Weathered oil for the experiments was produced by evaporating fresh Dilbit for 24 hours at room temperature in shallow pans 45 cm wide by 65 cm long. The oil was 8 mm deep initially. After 24 hours under very light air flow, the oil had lost 19 weight percent. Weathered Dilbit was stored in sealed containers kept at 10°C. Bitumen from Imperial Oil's Cold Lake facility was used for the control trays.

The measurement of evaporation from a weathered oil sample on a wet shore substrate imposes some difficult experimental conditions. Up to 3500 gm of substrate was sometimes required to ensure that all of the spilled oil was held in the shore material. About 100 gm of oil was used to cover the model shore to a nominal depth of 1 mm. When the trays were flooded to simulate oil stranding at high tide, the total weight of the trays and contents was usually about 5000 gm. Dilbit is made up of about 30% gas condensate of which 50 to 60% may be lost during the pretest 24 hour weathering process. Thus the evaporative loss from the weathered Dilbit on the model shore will not exceed 10% of the spilled oil weight or perhaps 10 gm. One is faced with measuring a maximum 10 gm weight loss in a loaded tray weight of 5000 gm. In addition there will be coincident water evaporation from the wet substrate. These small weight changes were measured with a carefully regulated InterTechnology load cell connected to a micrologger and computer. A Vishay Instruments Model 2310 power supply and signal amplifier was used to power the load cell and amplify its output. This signal was digitized and stored at 5 minute intervals in a Campbell Scientific Model 21x micrologger. Periodically, the micrologger memory was downloaded to a desktop computer. Evaporative losses were measured at 10°C, 0°C, and -10°C for Dilbit and Bitumen spread on each of the shoreline types.

STUDY RESULTS

Data Analysis

Data accumulated by the micrologger contained noise associated with the cold room fans and other sources of vibration. Some of this noise could be removed from the data by taking hourly running averages about each data point. Each half hourly and hourly data point for the hundred hour runs was then extracted for graphing and further analysis. A typical graph of weight loss obtained for Dilbit on shore type 3 (a well graded medium to fine grain sized sand) is shown in Figure 1. A common feature of all such graphs was the apparent change in slope at about 50 hours. We believe that at this point of the experiment, most of the light ends of the oil have evaporated and the continuing weight loss is

FIGURE 1 DILBIT ON SHORE TYPE 3

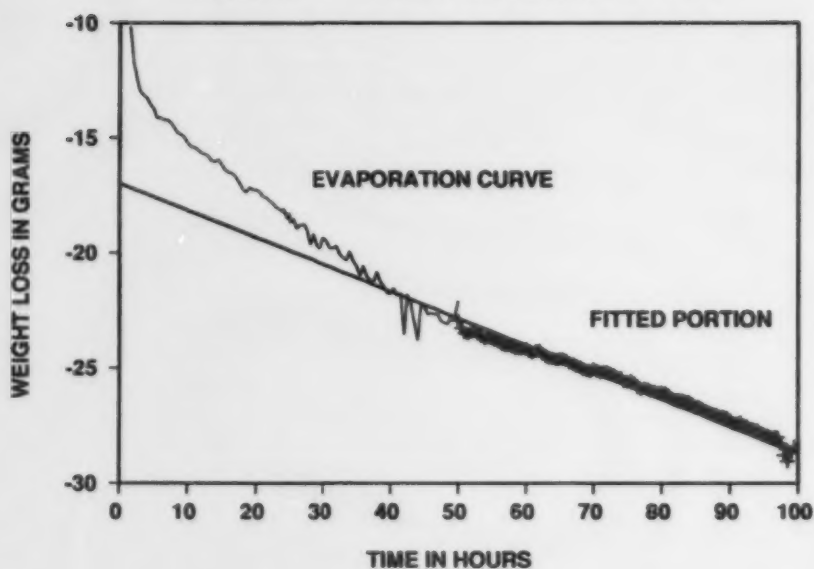
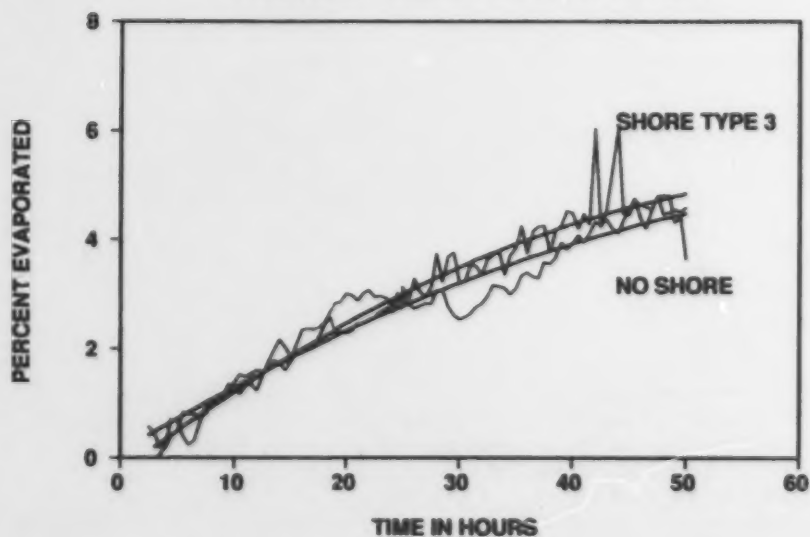


FIGURE 2 DILBIT EVAPORATION

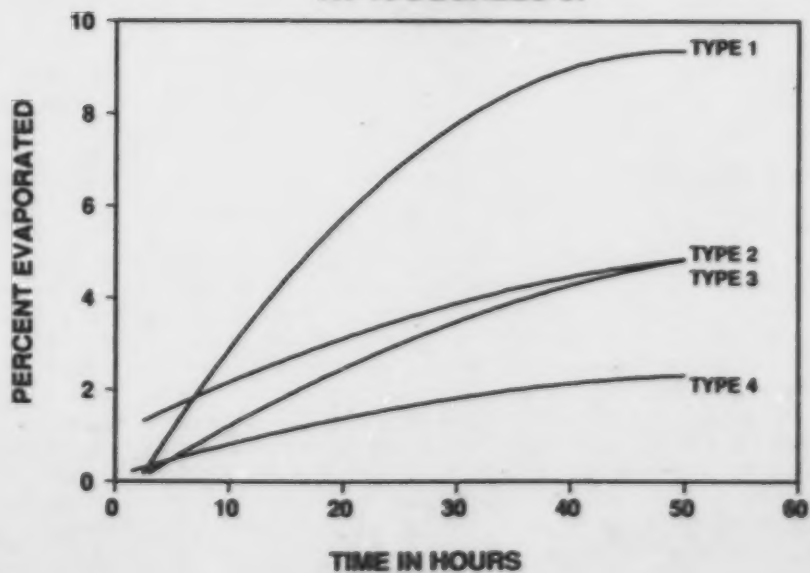


due primarily to water loss from the sands. To separate water loss from that due to oil evaporation, a first order equation was fitted to the data accumulated after the first 50 hours and then extrapolated back to the beginning of the experiment. Oil loss was deemed to be the difference between the fitted, extrapolated line and the measured weight loss curve for the first 50 hours of the experiment. The result of this procedure is shown in Figure 2 where the loss has been converted to percent of oil evaporated. Also shown on Figure 2 is a graph of the percent Dilbit evaporated for an experiment in which oil was evaporated from a tray with no shore material or water substrate. The similarity of the two curves appears to confirm the correctness of the analysis procedure. Both the derived data, which shows some scatter and the best fit second order curves are shown.

Shoreline Evaporation

The procedure described above was used to measure the evaporation of Dilbit which had been previously weathered for 24 hours, on four different shoreline materials. An example of one of these shoreline materials is shown in Figure 3. The photograph is of two trays with type 1 material, one tray covered with Dilbit, the other with Bitumen. This material contains rocks up to 5 cm across, clams and barnacles, and finer rock and shell fragments mixed with sand and clays. It came from the sheltered side of Rebecca Spit on Quadra Island.

Evaporation rates for Dilbit appear to depend on the type of shore substrate used in the experiments. This is apparent in Figure 4 which shows the results from several experiments conducted in a cold room at 10°C, a temperature which was chosen as being representative of a typical Fall or Spring shore environment. The graph shows the best fit second order line for each data set - the actual data has some scatter similar to that shown in Figure 2. The graph appears to suggest that evaporation is faster on shore materials that contain a wide variation in rock sizes and compositions such as types 1 and 2. In contrast, shore types 3 and 4 are both well sorted sands; shore 4 in particular consists of a fine sand containing some silt from the Oyster River on Vancouver Island. Oil stranded on these latter two materials was observed to penetrate approximately the top millimeter of shore, nevertheless leaving a uniform oil layer exposed to the air. Below about 1 mm the sands remained wet and impenetrable to the oil over the 4 day duration of the experiment. Shore materials of types 1 and 2 did not retain water as readily and the stranded oil on these shores penetrated further into them. In some experiments patches of oil seeped down to the wire mesh which supported these shore types. Such observations suggest that the evaporation is likely dependent upon the effective material area coated by the oil. Shore materials 1 and 2 had many exposed surfaces and open pore spaces in comparison to the smooth tightly packed surfaces of shores 3 and 4. Shoreline type 4 even appeared to retard evaporation slightly compared to that on calm open water (compare the graphs of Figure 2 with those of Figure 4), perhaps because the oil is tightly bound into the upper millimeter of the sand.

FIGURE 3 TYPICAL SHORELINE MATERIAL**FIGURE 4 EVAPORATION FROM VARIOUS SHORES AT 10 DEGREES C.**

A number of runs conducted at 0°C and at -10°C always yielded evaporation rates lower than those shown in Figure 4 for each shore type. However, the scatter in the data increased and it was not possible within the experimental error to rank the shore types.

CONCLUSIONS

The evaporation of a bitumen / condensate mix from model shorelines has been measured in the laboratory. This information will be used to improve oil spill trajectory model prediction of shoreline oiling and persistence. The data indicates that evaporation will be more rapid on shore material which provides a large surface area for the oil. Well sorted or compacted sands which hold water also trap the oil in a shallow layer and appear to slow evaporation perhaps to less than what would occur on open calm water.

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MESO-SCALE FLUME TEST FOR LABORATORY WEATHERING OF OIL

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ABSTRACT

When an oil is spilt at sea, several weathering processes take place simultaneously. These processes can either be studied isolated ("stepwise") in small-scale laboratory investigations or in connection to experimental field trials with oil at sea. To get the opportunity to study these processes simultaneously, under controlled conditions, a meso-scale flume basin has recently been built. This presentation deals mainly with the construction and practical use of the meso-scale system. The few preliminary results that are presented serve only as examples of use of the flume in connection with the initial studies.

The meso-scale flume basin was given the shape of a skating rink, with a wave generator and wind-tunnel as the main devices for creating different weather conditions. It is our goal that the meso-scale flume test will be a "link" between small-scale laboratory studies and field studies, and becomes a supplementary source for data input to existing models for prediction of oils behaviour at sea.

The preliminary tests with the meso-scale flume basin have been promising.

BACKGROUND

When an oil slick is exposed to weathering at sea, the physico-chemical properties of the oil may be drastically changed. These changes may have a great influence on the effectiveness of both mechanical recovery systems, thermal, biological and chemical oil

spill combat methods. A better understanding of these weathering processes and their effect on different oil types is therefore important to increase the efficiency of all existing response methods and for defining their limitations.

Crude oil is a complex mixture of hydrocarbons and non-hydrocarbons which commonly are classified into the following groups: saturates (e.g. alkanes and naphthenes), aromatics, resins (NSO-compounds) and asphaltenes. Small differences in composition between different crudes can greatly affect the physical properties and hence the formation and stability of water in oil(w/o)-emulsions. It is believed that especially the content of wax and asphaltenes play an important role in the formation and stability of w/o-emulsions (e.g. Mackay, 1987).

When studying weathering effects on different oils, it is important to expose the oil to as realistic a weathering regime as possible. A recently constructed meso-scale flume basin presented here will hopefully be a "link" between the small-scale ("stepwise") weathering procedure already established at IKU (Daling et al. 1990) and large-scale testing of oil weathering properties in the field.

OBJECTIVE

The main objective for construction and building of the meso-scale flume basin was to establish a system for preparative weathering of oils, taking into account the different weathering processes (evaporation, w/o-emulsification etc.) and thereby make it possible to study these processes simultaneously instead of on an individual basis as in the small-scale laboratory investigations.

The aim was to calibrate the meso-scale flume system to oil properties data predicted at 5-10 m/s wind and sea state 3-4 by numerical weathering modelling, based on standardized "stepwise" laboratory data. In this way the meso-scale system may be an important supplement to existing laboratory procedures, as data input to numerical models used for predicting oils' behaviour at sea.

METHODOLOGY FOR PREDICTION OF OILS' WEATHERING AT SEA

An approach for characterizing the behaviour of oils spilled on the sea has during the last years been developed at IKU, Sintef-group. The approach includes an extensive "stepwise" laboratory investigation of an oil's properties when exposed to weathering (Daling et al. 1990; Daling and Brandvik. 1991).

The experimental data from these standardised "stepwise" laboratory investigations of the oils are transferred to field conditions in a numerical weathering model. The model predicts the rate of weathering processes at sea under different weather conditions. The algorithms in the model are established on the basis of theoretical considerations, as well as empirical data from field trials with oil spills. Figure 1 gives a schematic diagram of the laboratory data that are put into the model and the properties predicted by the model.

The computer system displays an user-friendly manual (standard charts) which predicts the development of relevant oil properties with time. The methodology has clearly demonstrated that the type of oil is essential for the rate of the weathering processes in addition to the environmental conditions (Daling and Brandvik 1991).

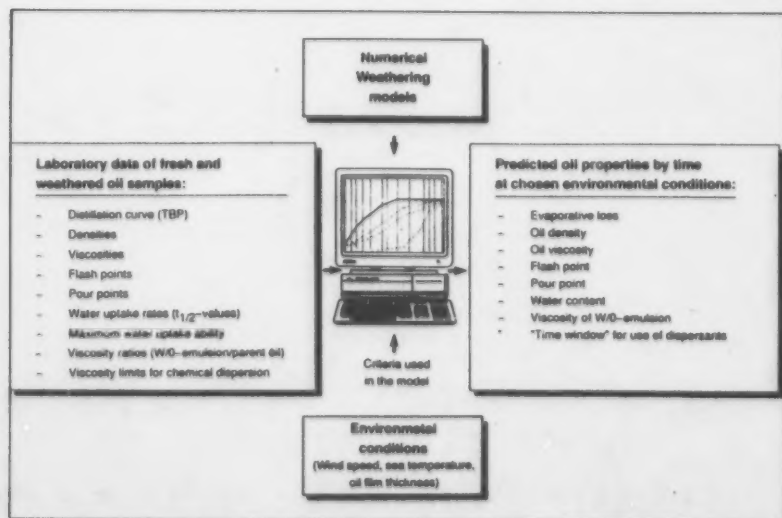
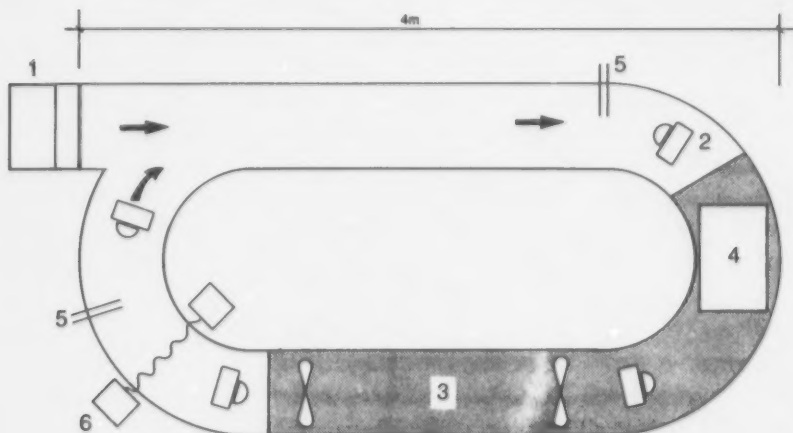


Figure 1: Schematic diagram of the data input to the model and the predicted output oil properties.

DESIGN AND CONSTRUCTION OF THE FLUME BASIN

The SINTEF-group has earlier performed weathering studies in a flume basin with the presence of ice (Ø .Johansen et al. 1990). That flume consisted of two parallel tracks connected in each end and separated with a narrow barrier in the middle. Due to the sudden turn at each end, it was difficult to circulate the ice, and the oil had a tendency to stick to the walls (wall effect).

In the construction of the new meso-scale flume basin we decided to use the same principle. However, to minimize the wall effect, the two parallel tracks were separated by a distance of 1 meter giving it the shape of a skating rink (figure 2).



1. Wave generator
2. Pumps (Water circulation)
3. Wind-tunnel
4. Photolysis (sun-lamp)
5. Sub-surface sampling
6. Transmittance meter

Figure 2: Schematic drawing of the meso-scale flume basin (seen from above).

Plexiglass (methyl polymethacrylate) was chosen as the building material. It has a relatively low cost, is flexible and it gave us the opportunity to visually observe the whole water column during the experiments.

The total length of the basin is approximately 9 meters and the width is 0.5 meters. When it is filled with seawater to a depth of 0.4 meters the volume is approximately 1750 liters. To achieve a basic and uniform circulation of the water, three (sub-sea) water pumps are installed at the bottom of the basin. Two adjustable fans are installed in a wind-tunnel and wind with different strength (speed) can be created by these two fans. The wind is continuously monitored by a wind gauge. An adjustable wave generator can create waves with different frequencies and different wave height (e.g. breaking or non-breaking waves). If photooxidation of the oil is required, a sun-lamp will provide radiation for artificial photolysis.

Oil samples for analysis can be taken directly from the surface. Sub-surface water samples for analysis of, for instance, natural dispersion of oil can be taken at various depths at two different places in the flume. To get the best relative quantification of the natural dispersion in the flume, the samples are preferably taken at a sampling point shortly before the oil is exposed to the breaking waves (see figure 2). Natural dispersion can also be continuously monitored by a transmittance meter installed in the water.

EXPERIMENTAL TEST CONDITIONS

The whole flume basin is placed in a temperature-adjustable cooling room (capacity for controlling the temperature between -30°C and $+50^{\circ}\text{C}$). During the preliminary tests the water and air temperatures were 13°C . 1750 litres of seawater (salinity 3.3‰) was used in each test. 9 litres of fresh, stabilized crude was carefully added to the surface, giving a film thickness of approximately 2 mm. The circulation speed was approximately 2 min. per lap. The crudes were weathered for 72 hrs with sampling of surface oil and sub-surface samples at given intervals. The samples were subjected to several analyses (water content, viscosity, degree of evaporation, natural dispersion etc.).

Initially, three calibration experiments were performed, resulting in appropriate settings for wind strength, wave frequency and wave height.

PRELIMINARY RESULTS AND DISCUSSION FROM THE INITIAL STUDIES

The main intention of this paper is to give a preliminary information about the meso-scale flume basin and to present its potential for use in studies of oils' behaviour at sea. As an example of what has been done in the flume so far, and to get a better understanding of the possibilities for future use of the flume, some examples of results from the preliminary studies of weathering of North Sea crudes are given below.

A. Evaporative loss

Figure 3 presents a prediction chart for evaporative loss of a North Sea crude at sea. Into this chart we have plotted the evaporative loss for the same crude as obtained in the flume. The figure shows a good correlation between the predicted values (5-10 m/s wind speed) and the data from the flume experiment.

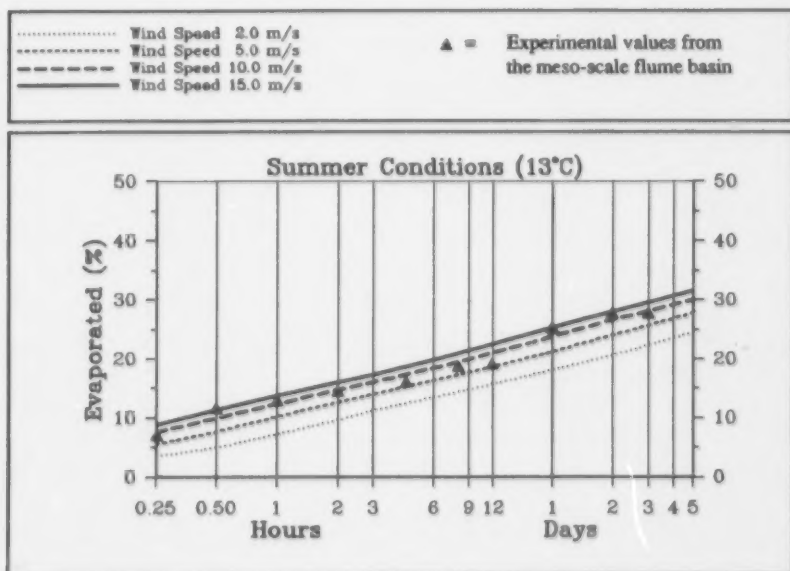


Figure 3: Standard chart for predicted evaporative loss of a North Sea crude, with a plot of the experimental values for the same crude as obtained in the meso-scale flume basin.

B. Water uptake (w/o-emulsification).

Figure 4 presents the predicted water uptake vs time for a North Sea crude at sea, based on "stepwise" laboratory data, and the water uptake data for the crude as obtained in the flume experiment.

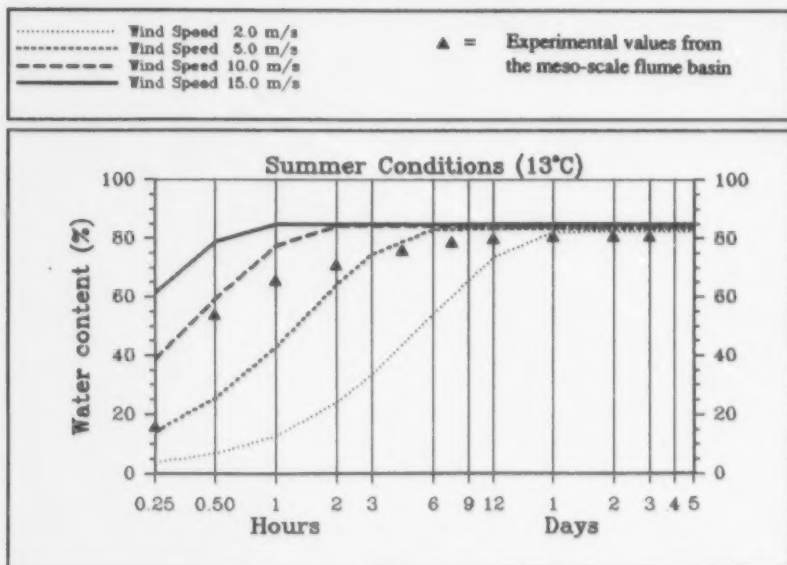


Figure 4: Standard chart for predicted water uptake for a North Sea crude, with a plot of the experimental values from the flume test.

A comparison of the data obtained in the flume test to the predicted values, reveals that the water uptake kinetics are in good agreement with the predictions (5-10 m/s wind speed). The maximum water uptake is, however, about 5% lower than the predicted values.

C. Viscosity

The viscosity of a w/o-emulsion is dependant of the water content of the emulsion and the viscosity of the water-free parent oil (e.g. Mackay et al. 1980). Figure 5 shows a plot of the viscosity of the emulsions for a North Sea crude obtained in the flume. The

predictions are based on a "stepwise" laboratory investigation of the same crude.

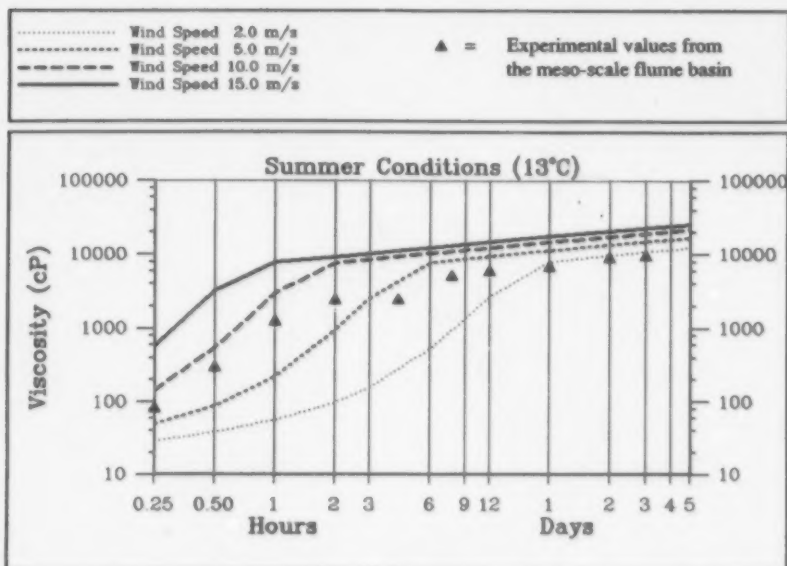


Figure 5: Standard chart for prediction of viscosity of emulsions for a North Sea crude, with a plot of the experimental values obtained in the flume.

The figure shows that the viscosity values from the flume are slightly lower than the predicted values (5-10 m/s wind speed) after 2-3 days of weathering. This difference is mainly due to the difference in the maximum water-uptake ability between the predicted and the experimental values. If we put into the weathering model a water uptake similar to what was obtained in the flume experiment (as plotted in figure 4), we will get a prediction in quite good correlation with the experimental values.

D. Natural dispersion

If there is sufficient energy on the surface and the oil has not become too viscous, the waves will break up an oil spill to droplets (from 1 to 1000 μm) and mix them into the water column.

This happens mainly when breaking waves are present (wind speed higher than 5 m/s). The largest droplets may resurface and form blueshine behind the spill. The smallest droplets will, due to current, vertical and horizontal diffusion, be spread and quickly diluted in the water column. We call this process natural dispersion.

Figure 6 shows the natural dispersion for four different North Sea crudes as obtained in the meso-scale flume basin.

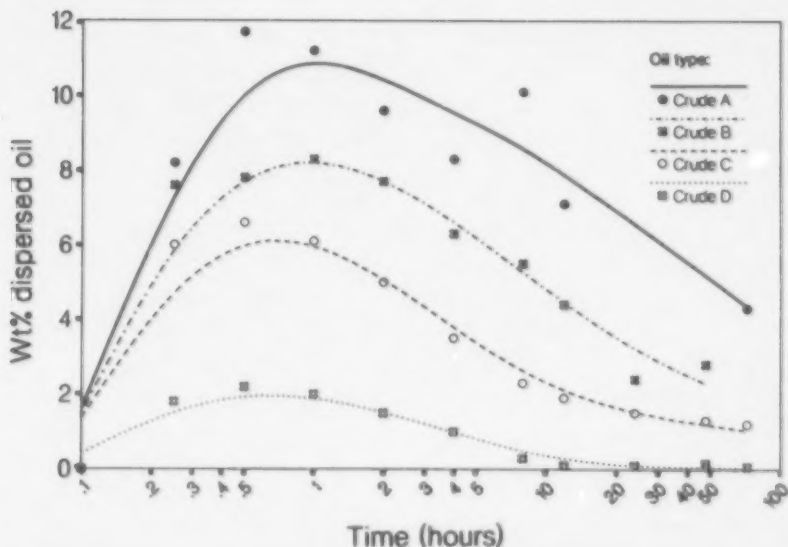


Figure 6: Natural dispersion vs time for four North Sea crudes, obtained in the flume test.

The natural dispersion is dependant on a number of factors such as degree of weathering, type of oil, viscosity of oil/emulsion etc. In the flume experiments it seems to reach a maximum between 0.5 and 1 hour of weathering on the surface, and there seems to be a good correlation between the degree of natural dispersion of a crude and the measured viscosity of the parent w/o-emulsion.

CONCLUSION AND FUTURE PLANS

The preliminary studies in the meso-scale flume basin have been promising. Taking into account the slightly reduced maximum water uptake, most of the experimental data have been close to the predicted values. The small differences in maximum water uptake between the experimental values from the flume and the predicted values, are most likely due to the differences in the energy input between the two laboratory methodologies. We believe that the rotating flask method (Mackay et.al, 1982) used for w/o-emulsion formation studies in the "stepwise" laboratory procedure, gives a slight overestimate of the maximum water uptake ability, due to a too high energy input. The meso-scale flume is probably a better approach to simulation of field conditions. It is therefore our intention, that in the near future, data from the meso-scale flume basin will be used as a supplementary input to numerical weathering models.

So far the meso-scale flume basin has been used only for weathering studies of crude oils under North Sea conditions. The meso-scale system has however a wide potential for use in other research studies, such as:

- * Weathering of surface oil in the presence of ice (arctic conditions).
- * Performance testing of oil spill chemicals including dispersants and emulsion breakers.
- * Bioremediation studies.
- * Mechanism studies (weathering processes, surfactant mechanisms etc.).

ACKNOWLEDGEMENT

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A HYBRID MODEL TO PREDICT THE ENTRAINMENT AND SUBSURFACE TRANSPORT OF OIL

by

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ABSTRACT

The entrainment of surface oil into the water column and its subsequent subsurface transport and dispersion are predicted by a hybrid analytic-numerical solution to the advective diffusion equation. Total oil or selected hydrocarbon component concentrations in the water column are predicted. Assuming that the principal mechanism for entrainment is due to breaking waves, the oil entrainment rate, is specified using Delvigne and Sweeney's (1988) empirically based algorithm. The subsurface transport model explicitly accounts for buoyant forces on dispersed oil by droplet size. Application of the model to an analytic test case and several hypothetical scenarios illustrates the model's utility.

1. INTRODUCTION

The vast majority of oil spill models currently available (Spaulding, 1988; Davidson and Lawrence, 1982; Huang and Monastero, 1982; Stolzenbach et al., 1977) focus only on the transport and fate of the surface slick. In these models oil dispersed into the water column is removed from the surface slick and the oil mass balance, by environmental compartment, is adjusted accordingly. There is no explicit treatment of the subsurface transport or resurfacing of dispersed oil (Elliott, 1986).

In situations where the impact of oil on marine resources in the water column is important, such as in natural resource damage assessments and chemical dispersant decision-making, one needs to have an estimate of the temporally and spatially varying oil concentration field to which biota are exposed. To perform such calculations Reed (1989), Anderson et al (1990, 1991), and ASA (1990) have employed a numerical, Lagrangian particle based model to predict the evolving oil concentration field. Oil particles (droplets) are injected into the water column from the surface slick and are advected and dispersed by the current field. The particles are assumed to be neutrally buoyant. Advection is calculated using the current data and turbulent dispersion is performed using a random walk technique. This procedure is extremely flexible and conceptually straight forward. The approach however is computationally intensive due to the large number of particles required to accurately represent the

concentration field. Resurfacing of entrained oil is generally not included.

This paper presents an alternative method to predict the oil concentration field in the water column. The approach is based on integral solutions to the convective diffusion equation and explicitly includes representation of the oil by droplet size. The general methodology is described in detail in Section 2. Analytic solutions for vertical oil concentration profiles are presented for both short and long times. The model is then applied to several test cases to illustrate its ability to reproduce known analytic solutions to the governing equation and to demonstrate its utility for practical application in spill models.

2. FORMULATION OF ENTRAINMENT AND SUBSURFACE OIL CONCENTRATION MODEL

Entrainment

The entrainment (or dispersion) of oil from the sea surface into the water column is based on Delvigne and Sweeney's (1988) empirical formulation. This approach assumes that breaking waves are the principal mechanism responsible for dispersing oil into the water column and that the oil slick is broken into a large number of droplets of varying sizes in the process (Aiyavamudan et al., 1982; Bouwmeester and Wallace, 1986; Delvigne et al., 1987; Milgram et al., 1978; Nilsen et al., 1985; Raj, 1977). They define the entrainment rate as a function of oil droplet or particle size, d , by

$$Q_d = C^* D_d^{0.57} S F d^{0.7} \Delta d \quad (1)$$

where

- Q_d - entrainment rate of oil droplets, with droplet sizes in an interval Δd around d , per unit surface area ($\text{kg m}^{-2} \text{sec}^{-1}$)
- C^* - empirical entrainment constant which depends on oil type and weathered state (Table 1)
- D_d - dissipated breaking wave energy per unit surface area (J m^{-2})
- S - fraction of sea surface covered by oil ($0 < S < 1$)
- F - fraction of sea surface hit by breaking waves "white caps" per unit time (sec^{-1})
- d - oil particle diameter (m)
- Δd - oil particle diameter interval (m)

The dissipated wave energy is expressed in terms of the root mean square (rms) wave height by

$$D_d = 3.4 \times 10^{-3} \rho_w g H_{rms}^2 \quad (2)$$

where

- ρ_w - density of seawater (kg m^{-3})
 g - gravitational constant (m sec^{-1})
 H_{rms} - rms value of the wave height (m)

The energy dissipation rates are typically in the range of 10^3 to $10^4 \text{ J m}^{-3} \text{ sec}^{-1}$ for breaking waves and two to three orders of magnitude lower for the sea surface layer under nonbreaking conditions.

The fraction of the sea surface impacted by breaking waves per unit time, F , (sec^{-1}) is parameterized as

$$F = 0.032(U_w - U_T)/T_w \quad (3)$$

where

- U_w - wind speed at 10 m above the sea surface (m sec^{-1})
 U_T - wind speed threshold for onset of breaking waves ($\sim 5 \text{ m sec}^{-1}$)
 T_w - significant wave period (sec)

If the wind speed is less than the threshold value then $F = 0$ and no oil is entrained.

The oil droplet size range typically varies from 2-1600 μm (diameter) with most of the oil volume in the 10-300 μm droplet size range. The maximum droplet size, d_{max} , depends on the viscosity of the oil, ν , and the energy dissipation rate, e , ($\text{J m}^{-3} \text{ sec}^{-1}$) according to the formula

$$d_{\text{max}} = C_1 \nu^{0.34} e^{-0.5} \quad (4)$$

where C_1 is an empirical constant based on mixing energy levels (Delvigne and Sweeney, 1988). This relationship is restricted to non-emulsified oils.

Based on full scale tank observations breaking wave events rapidly distribute the oil in the near sea surface zone, typically restricted to an intrusion depth, z_m , of

$$z_m = (1.5 \pm 0.35)H_b \quad (5)$$

where H_b is the breaking wave height.

The entrainment rate given in Eq 1 is for one size class, $d - \Delta d/2$ to $d + \Delta d/2$. To obtain the total entrainment rate Eq 1 must be integrated over all particle sizes extending from the minimum to maximum oil droplet sizes, typically 10 to 300 μm .

Subsurface Oil Concentration

The distribution of oil concentration in the water column can be determined by solving the convective-diffusion for each droplet size class.

$$C_t - wC_z = D_1C_{xx} + D_2C_{yy} + DC_z + Q \quad (7)$$

where the subscripts indicate derivatives with respect to the given variable: t - time, x, y - horizontal distance and z - vertical distance. C is the oil concentration for a given droplet size range $d \pm \frac{1}{2}\Delta d$ and w is the terminal rise velocity (Stokes) of oil droplets expressed as

$$w = \frac{d^2 g}{18 \nu} \frac{(1 - \rho_o / \rho_w)}{\nu} \quad (8)$$

where

- d - droplet diameter (m)
- ρ_o - density of oil (kg m^{-3})
- g - gravitational constant (m sec^{-2})
- ρ_w - density of sea water (kg m^{-3})
- ν - viscosity of sea water ($\text{m}^2 \text{sec}^{-1}$)

D_1 and D_2 are the x and y directed horizontal turbulent dispersion coefficients, respectively and D is the vertical turbulent dispersion coefficient.

The source term Q is expressed as

$$Q = \frac{Q_d}{z_m} H(t) [H(z) - H(z - z_m)] \delta(x) \delta(y) \quad (9)$$

where δ is the delta function and H is the Heaviside function. This formula assumes oil is dispersed into the water column from a unit area on the sea surface and instantaneously mixed over the upper z_m of the water column, where z_m is given by Eq 5.

The formulation given in Eq 7 assumes no horizontal advection of oil. The case with advection however can be approximated by moving the predicted oil distribution at the observed current velocity. This approach however requires that the advective velocity be uniform over the water column. Equation 7 also assumes that the horizontal and vertical turbulent diffusivities are constant but unequal. In practice Eq 7 is solved for each oil droplet size class. Summation over all oil droplet size classes gives the total oil concentration in the water column. If dispersant treatment of surface oil needs to be addressed this can readily be achieved by suitably altering the source function and rise velocity, w ,

to simulate chemically treated oil droplets.

The boundary conditions on Eq 7 assume no transport of oil through the sea surface and that the oil concentration approaches zero as $z \rightarrow \infty$. Note that the use of the Heaviside function in the source term, Q , approximates the mechanics of the entrainment process. The lower boundary condition is reasonable as long as the water column depths are greater than about 20 m and the oil droplets are assumed to be buoyant. With Q expressed using Eq. 9 oil is entrained at a rate Q_d starting at $t = 0$. In the event that oil entrainment is only active over a time increment from $t = 0$ to $t = t_0$ the oil source function in Eq 9 must be modified to

$$Q = \frac{Q_d}{z_m} [H(t) - H(t-t_0)] [H(z) - H(z-z_m)] \delta(x) \delta(y) \quad (10)$$

The solution to Eq 7 with the source function given by Eqs 9 or 10 can be expressed as

$$C(x,y,z,t) = A \int_0^{t^*} \int_{-t^*}^t e^{-\frac{R_1^2 + (\zeta - z - w\tau)^2}{4D\tau}} \frac{d\tau d\zeta}{\tau\sqrt{\tau}} \quad (11)$$

$$\text{where } t^* = \begin{cases} t & \text{if } t < t_0 \\ t_0 & \text{if } t > t_0 \end{cases}$$

and

$$A = \frac{Q}{8\pi^{3/2} z_m \sqrt{D_1 D_2 D}} \quad (12)$$

$$R_1^2 = \frac{D}{D_1} x^2 + \frac{D}{D_2} y^2 \quad (13)$$

The case of an arbitrary source function $Q(t)$ with arbitrary start and end times can be approximated by generalizing the above procedure using linear superposition.

The solution to Eq. 11 gives the oil concentration for a given oil droplet size. To predict the total oil concentration Eq 11 must be integrated over the entire oil droplet size range. In performing this integration, the source function Q must be included inside the integral as it depends on droplet size (see Eq 1).

If the oil concentration is integrated over space and time it is observed that

the oil mass decreases exponentially with radius from the source. The mass of oil in the cylindrical water column of radius R is

$$M(R,t) = \int_0^{2\pi} \int_0^R \int_0^{\infty} C(x,y,z,t) dz r dr d\theta = M(t) - M_R(R,t) \quad (14)$$

Where $M(t)$ is the mass of oil in the entire water volume

$$M(t) = \frac{Q}{2z_m} \int_0^{z_m} \int_{t-t'}^t \operatorname{erf} \left(\frac{w\tau - \zeta}{2\sqrt{D\tau}} \right) d\tau d\zeta \quad (15)$$

where erf is the error function and $M_R(R,t)$ is the mass of oil in the water column beyond radius R . Assuming $D_1 = D_2 = D_h$

$$M_R(R,t) = \frac{Q}{2z_m} \int_0^{z_m} \int_{t-t'}^t e^{-\frac{R^2}{4\tau D_h}} \operatorname{erfc} \left(\frac{w\tau - \zeta}{2\sqrt{D\tau}} \right) d\tau d\zeta \quad (16)$$

where $\operatorname{erfc} = 1 - \operatorname{erf}$.

For $t \rightarrow \infty$

$$M_R = e^{-\frac{Rw}{2\sqrt{DD_h}}} = e^{-\frac{R}{R^*}} \quad (17)$$

where

$$R^* = 2 \frac{\sqrt{D_h D}}{w}$$

Equation 17 predicts that the majority of the oil mass is within several R^* of the origin. R^* increases as the oil droplet velocity decreases reflecting the increasing role of horizontal diffusion in dispersing the oil. When w is large however, horizontal dispersion is minimized since the oil droplets immediately return to the surface because of their buoyancy.

The solution to Eq 11 shows that the horizontal distribution of oil concentration has a Gaussian shape. For a fixed oil droplet rise velocity the horizontal concentration distribution is controlled by the dispersion coefficients D_1 and D_2 . If $D_1 = D_2$ the oil concentration contours are circular about the coordinate origin. The concentration contours become elliptic if D_1 is not equal to D_2 .

To develop insight into the vertical oil concentration distribution it is instructive to simplify Eq 7 by eliminating horizontal dispersion. In this case the governing equation becomes

$$C_t - wC_z = DC_{zz} + Q \quad (18)$$

where

$$Q = \frac{Q_d}{z_m} [H(z) - H(z - z_m)] [H(t) - H(t - t_0)] \quad (19)$$

The solution for oil concentration is given by

$$C(z, t) = \frac{Q_d}{2\sqrt{\pi} z_m \sqrt{D}} \int_0^{z_m} \int_{t-t}^t e^{-\frac{(\zeta - z - w\tau)^2}{4D\tau}} \frac{d\tau}{\sqrt{\tau}} d\zeta \quad (20)$$

The corresponding solution for the total oil mass in the water column at time t is

$$M(t) = \int_0^\infty C(z, t) dz = \frac{Q}{2z_m} \int_0^{z_m} \int_{t-t}^t \operatorname{erfc} \left(\frac{w\tau - \zeta}{2\sqrt{D\tau}} \right) d\tau d\zeta \quad (21)$$

It is helpful in understanding the solutions to these integral equations to explore the asymptotic behavior for large and small times. We define two typical time scales

$$T_1 = z_m^2/4D \quad \text{and} \quad T_2 = 4D/w^2$$

T_1 represents the time scale for a neutrally buoyant oil droplet to diffusive through the breaking wave mixed zone z_m . T_2 is a time scale based on the relative contribution of diffusion to buoyant effects on an oil droplet. A third time scale can be introduced as $T_3^2 = T_1 T_2 = (z_m/w)^2$. T_3 is the time scale for a buoyant oil droplet with rise velocity w to advect through the breaking wave mixed zone.

In the presentation to follow large t assumes that $t > \max(T_1, T_2)$ and therefore $t > T_3$. Small t on the other hand indicates that $t < \min(T_1, T_2)$ and therefore $t < T_3$. Large values of t represent the case where the oil droplet rise rate is small and hence long times are required for the droplets to reach the sea surface. Small t represents the opposite case.

The solutions to Eqs 20 and 21 will now be discussed for small and large t .

Small t

The concentration at the surface $z = 0$ for small values of t is

$$C(0, t) = \frac{Q}{2z_m} \left(1 + \frac{4}{3\sqrt{\pi}} \sqrt{\frac{t}{T_2}} \right) \quad (22)$$

If $\sqrt{Dt} \ll z \ll z_m - \sqrt{Dt}$, which corresponds to the region near the center of the well mixed zone, the concentration becomes

$$C(z, t) = Q/z_m \quad (23)$$

At $z = z_m$ the concentration becomes

$$C(z_m, t) = \frac{Qt}{2z_m} \left(1 - \frac{4}{3\sqrt{\pi}} \sqrt{\frac{t}{T_2}} \right) \quad (24)$$

For $z \gg z_m + \sqrt{Dt}$ the concentration is exponentially small

$$C(z, t) = e^{-\frac{z^2}{4Dt}} \quad (25)$$

Figure 1 shows the oil concentration profile with depth for small t . The concentration increases with depth and reaches a maximum in the wave mixed zone. It then decreases as z increases and exponentially approaches zero below z_m .

For small t the oil mass in the water column is expressed as

$$M(t) = Qt \left[1 - \frac{1}{3\sqrt{\pi}} \sqrt{\frac{t}{T_1}} - \frac{1}{4} \frac{t}{T_3} \right] \quad (26)$$

where T_1 and T_3 are described above.

Large t

For large values of t the oil concentration can be expressed by

$$C(z, t) = C(z, \infty) - \frac{Q}{\sqrt{\pi}w} \sqrt{\frac{T_2}{t}} e^{-\frac{t}{T_1}} e^{-\frac{z^2}{2z_1}} \quad (27)$$

where the concentration for $t \rightarrow \infty$ is given by

$$C(z, \infty) = \begin{cases} \frac{Q}{w} \left[1 - \frac{z}{z_m} + \frac{z_1}{z_m} (1 - e^{-\frac{z}{z_1}}) \right] & \text{if } z < z_m \\ \frac{Q}{w} e^{-\frac{z}{z_1}} \frac{z_1}{z_m} (e^{\frac{z_m}{z_1}} - 1) & \text{if } z > z_m \end{cases} \quad (28)$$

where $z_1 = D/w$

The solution to Eq. 27 is presented in Figure 1. For $t \rightarrow \infty$ the oil concentration is maximum at the surface with a value of Q/w and decreases exponentially with depth with a scaling parameter of z/z_1 .

When t is large the oil mass in the water column can be expressed as

$$M(t) = Q\left(\frac{1}{4}T_2 + \frac{1}{2}T_3\right) - \frac{QT_2^2}{2\sqrt{\pi}\sqrt{T_1}t} e^{-\frac{t}{T_2}} \left(e^{\frac{z_m}{2z_1}} - 1\right) \quad (29)$$

when $t \rightarrow \infty$ the oil mass becomes

$$M(\infty) = Q\left(\frac{1}{4}T_2 + \frac{1}{2}T_3\right) \quad (30)$$

Equation 29 shows that for large t the mass exponentially approaches the maximum mass with the time scale controlled by T_2 .

Figure 2 shows the oil mass in the water column versus time. The mass entrained in the water column is given by the straight line, which is the product Qt . The dashed line shows the full solution to Eq 21 and asymptotically approaches a maximum value of $M(\infty)$. The difference in mass between the two curves represents the mass of oil returned to the surface by the buoyancy of the oil droplet.

It is of interest to estimate the oil concentration and mass when t is larger than t_0 . This represents the time period after oil entrainment has ceased. Buoyant effects however still return oil to the sea surface.

The oil concentration profile at $t = t_0$ is given by Eq 27. For small values of Δt ($\Delta t \ll t_0$) the profile is depicted in Figure 3, but has no simple analytic expression.

If $t \gg t_0$ (large Δt) then the concentration can be expressed by

$$C(z,t) = \frac{Q}{w\sqrt{\pi}} \sqrt{\frac{T_2}{t}} e^{-\frac{t}{2t_1}} e^{-\frac{t}{T_2}} \left(e^{\frac{z_m}{T_2}} - 1\right) \quad (31)$$

As shown in Figure 3 the concentration for this case decreases continuously with depth.

The dispersed oil mass for small Δt can be expressed as

$$M(t) = M(t_0) - \frac{Q\Delta t}{2} \left[1 + \operatorname{erf} \sqrt{\frac{t_0}{T_2}} - \frac{2}{3\sqrt{\pi}} \sqrt{\frac{\Delta t}{T_1}} - \frac{2}{5} \frac{\Delta t}{T_3} \sqrt{\frac{\Delta t}{T_1}} \right] \quad (32)$$

where $M(t_0)$ is the oil mass in the water column at $t = t_0$.

For large values of Δt

$$M(t) = M_0(t) \frac{2z_1}{z_m} \left(e^{\frac{z_m}{2z_1}} - 1\right) \quad (33)$$

where $M_0(t)$ is given by:

$$M_0(t) = \frac{Q\sqrt{T_2}}{2\sqrt{\pi}} \int_{t_0}^t \frac{1}{\sqrt{\tau}} e^{-\tau/T_2} d\tau = \frac{QT_2}{2\sqrt{\pi}} \sqrt{\frac{T_2}{t}} e^{-\frac{t}{T_2}} \left(e^{\frac{t_0}{T_2}} - 1 \right) \quad (34)$$

The solution of Eq 32 is shown in Figure 4. For the case depicted t_0 is less than the time required to achieve the steady state mass in the water column $M(\infty)$ and hence the mass reaches a maximum value of $M(t_0)$. For times greater than t_0 the mass in the water column decreases with time reflecting the return of dispersed oil to the sea surface by buoyant effects.

3. IMPLEMENTATION IN SPILL MODEL

Since there are potentially a large number of spilletts, or parcels of oil that are used to define a given spill scenario, each undergoing independent weathering and transport, a procedure was required to predict the oil concentration in the water column for an actual spill release using the integral solution given above. To simplify the presentation the case of one spillet being released, transported, and weathered will be discussed. Generalization of the procedure to multiple spilletts will then be outlined.

After a spillet is released from the source it drifts, spreads, evaporates, and emulsifies according to the specified weathering algorithms (Spaulding et al., 1989, 1991). The mass of oil dispersed into the water column is calculated by multiplying the entrainment rate per unit area, Q_d , by the area of the slick. The breaking wave height and period necessary to calculate Q_d are estimated using the US Army Engineers Shore Protection Manual (CERC, 1984) wave model. Wind data are derived from a meteorological model or observations. The fetch is based on the geometry of the study area and the distance to the closest land point upwind of the spillet (along the wind direction).

Equation 11 is analytically integrated in space and numerically integrated in time using a trapezoidal procedure to predict the oil concentration distribution for a selected time increment. In the next increment of time more oil may be dispersed into the water column at a different rate Q_d . Equation 11 is again integrated to predict the concentration resulting from the most recent lot of entrained oil and then added to the oil concentration from the previous lot of dispersed oil at the present time. This process is repeated to predict the dispersed oil concentration in the water column for arbitrary oil entrainment rates from the surface slick.

As long as the surface oil slick and underlying water column are advected at the same rate/direction the above procedure can be used to predict the evolution of the dispersed oil concentration field. It is well known however that there is strong relative motion between the surface slick and the underlying water column (Stolzenbach et al., 1977; Elliott, 1986). The surface slick tends to more closely follow the wind than the near surface waters. The resulting relative motion between the oil slick and the near surface breaking wave mixed zone constantly exposes clean water to the surface slick. To represent this process and

still retain the analytic integral solution procedure, oil is dispersed from the surface slick to the water column initially underlying it until the plan view, areal overlap between the surface slick and the underlying water column is less than some predetermined value, say 20%. At this point a "new water column" located directly below the surface slick is designated to receive the dispersed oil. The initially contaminated water column is advected and dispersed but no longer receives oil from the surface slick. As the spill evolves the surface slick spawns oil contaminated water columns due to its relative advection over the underlying water. The larger the relative motion the more oil contaminated water columns generated. In the case of no relative motion only one water column with dispersed oil is generated.

The oil concentration in the water column at any time can be determined by summing the concentrations from the individual oil impacted water columns. The sum of the oil mass in these water columns is equal to the total amount of oil initially dispersed minus that returned to the surface through buoyant action on the oil droplets.

A scenario that sometimes occurs is that oil is entrained into the water column by a strong wind event. The surface slick moves away from the water column in which the oil was initially entrained. As the wind dissipates after the passage of the strong wind event the entrained oil returns to the surface because of a reduction in the near surface zone mixing energy and the buoyancy of the dispersed oil droplets. To simulate this situation the mass of oil returned from the water column to the surface is predicted and a surface spilllet created to represent the resurfaced oil. The areal extent of the resurfaced oil corresponds to the size of the oil contaminated water column.

The procedure for creation of subsurface water columns and surface slicks can be generalized to handle an arbitrary number of spilllets defining a complex time dependent spill. This process, while conceptually simple, can rapidly generate a large number of contaminated water columns and surface (and resurfaced) spilllets. This (computational) problem can be controlled by individually aggregating surface and subsurface oil when they are close together (e.g. overlapping).

Presentation of the dispersed oil concentration is normally shown in terms of oil concentration contours (horizontal) for fixed vertical slices in the water column. In practice the oil concentration in contaminated water columns are spatially interpolated and contoured to show the concentration field. To assure that mass is not created during this contouring process the total mass of oil in the contoured data set is calculated and compared to the net amount of oil entrained from the surface spilllets. The contoured oil concentration data is then scaled by the mass fraction (dispersed oil mass/original mass based on contoured data) to estimate the actual concentrations.

4. MODEL APPLICATION

To validate the methodology and assure that the numerical implementation was correct the model was applied to predict the vertical concentration distribution in the water column versus time resulting from an instantaneous point

release at the sea surface. The vertical diffusion coefficient was assumed constant at $10 \text{ cm}^2 \text{ sec}^{-1}$ (Thorpe, 1984). Horizontal diffusion was assumed to be zero. The analytic solution for this case is given in Csanady (1973). To replicate the conditions assumed in the analytic solution the source strength was constant over a short time interval and the wave mixed depth, z_m , was assumed to be extremely small. The entrained oil was assumed to be neutrally buoyant. Figure 5 shows a comparison between model predictions and the analytic solution 0.5, 1, and 3 days after the release. The model predictions are in very good agreement with the analytic results.

As examples of more practical cases simulations of an instantaneous spill of 1400 metric tons of oil in the presence of a uniform 6 m sec^{-1} wind (18 cm sec^{-1} surface drift) and no mean ocean current were performed for neutrally buoyant (no resurfacing oil) and typical oil droplet size (with resurfacing oil) distributions. The horizontal and vertical diffusivities were set to $5 \text{ m}^2 \text{ sec}^{-1}$ and $10 \text{ cm}^2 \text{ sec}^{-1}$, respectively. The wave mixed depth, z_m , was set at 2 m. The oil entrainment rate for these cases was assumed constant. For the neutrally buoyant case oil droplets did not resurface while for the observed oil droplet distribution resurfacing was driven by the buoyancy of the droplets.

Figures 6 and 7 show plan view (sea surface) and a vertical-longitudinal section view of the oil concentration field one day after the release for the neutrally buoyant and typical droplet distribution cases, respectively. In both cases the relative motion of the surface slick to the underlying water column generates an oil concentration plume upwind of the leading edge of the slick. The oil concentrations are highest at the surface and decrease with depth. They also decrease with distance in the wake of the slick. This longitudinal decrease in concentration is caused by horizontal and vertical dispersion of the oil.

Comparing the two simulations the neutrally buoyant case (without resurfacing) (Figure 6) has higher oil concentrations, by approximately a factor of 2, than for the typical oil droplet distribution case (with resurfacing) (Figure 7). The peak concentrations for the neutrally buoyant case (Figure 6) are located at -1 m . For the "with resurfacing" case the peak concentrations are at the surface. The difference between the two cases is a direct result of resurfacing of buoyant oil droplets.

The effect of resurfacing oil can also be clearly seen in the surface oil concentration contour plots shown at the top of Figures 6 and 7. The surface oil concentration contours upwind from the leading edge of the surface slick shows a much stronger spatial gradient for the non resurfacing case than for the resurfacing case. The oil resurfacing process acts to redistribute oil in a plume trailing the leading edge of the surface slick. This result is exactly the same as obtained by Elliott's (1986) shear diffusion model of oil spreading and is in good qualitative agreement with his field experiments.

Figure 8 shows the cumulative percent (%) oil entrained for the with and without oil resurfacing cases. Without resurfacing the percent oil entrained increases monotonically with time. The oil entrainment rate per unit area is constant however because the surface area of the slick continues to increase the rate of oil entrainment increases. At the end of one day 32% of the surface slick is entrained. For the resurfacing case the mass of entrained oil initially increases

with time but asymptotically approaches a steady state level of 18% after 21 hours. After this time the rate of oil entrainment and the rate of oil return to the surface by buoyant effects are in balance and hence the oil mass in the water column achieves a steady state.

It is impossible to rigorously verify predictions of subsurface oil concentrations from the proposed model because of the lack of adequate field data on environmental forcing fields and subsurface oil concentrations for either experimental or actual spill events. Simulation results however indicate peak oil concentrations under non storm conditions on the order of 2 to 7 ppm. These are in reasonable agreement with the limited available data from actual spill events as summarized in Table 2. The model also correctly predicts the rapid decrease in oil concentration with depth observed in actual spills (Table 2, see also NRC, 1989).

5. CONCLUSIONS

The entrainment and subsurface transport and dispersion of oil in the water column is predicted using Delvigne and Sweeney's (1988) algorithm to describe the rate of oil input to the water column and an integral solution to the convective - diffusion equation to predict the subsurface oil concentration field. The modeling approach predicts the oil entrainment rates and concentration by oil droplet size. Summation over the observed droplet size range allows predictions of the total oil concentration in the water. Because of its explicit representation by droplet size, resurfacing of water column dispersed oil by buoyant effects can be accurately predicted. Through linear superposition techniques the methodology can be used for arbitrary temporally varying oil entrainment rates.

To predict the spatial and temporal evolution of the subsurface oil concentration field for a complex oil release scenario with differential motion between the surface slick and the underlying water column the concept of contaminated water columns is used. These water columns are generated as oil is dispersed into the water underlying a slick. If the surface slick advects away from the initially contaminated water column new contaminated water column(s) are generated. These contaminated water columns are advected based on the specified current field. Oil from these water columns may return to the surface because of the buoyancy of the oil droplets or new oil added if a surface slick passes over them again and entrainment takes place.

Contouring of the various contaminated water columns allows a picture of the total oil concentration in the water column to be obtained as a function of time. The dissolved hydrocarbon concentrations for selected components (e.g. toxic fractions) can also be approximated using equilibrium partitioning theory (Shiu et al., 1990) or a more complicated oil droplet size dependent dissolution algorithm (Spaulding et al., 1982; Johansen, 1992). The approach can also readily be extended to predict concentrations of chemically dispersed oil by adjusting the source strength at small droplet sizes to reflect the entrainment rate of dispersant treated oil. This chemically treated oil remains dispersed for long periods of time because of its small droplet size and slow rise velocities.

Because of its analytic basis the model provides a continuous

representation of the vertical and horizontal structure of oil concentration. The methodology is computationally efficient compared to a particle based approach since we must only follow tens to hundreds of water columns rather than thousands of particles to represent the subsurface oil. This computational advantage is quickly lost for practical spill simulations if aggregation of contaminated water columns in close proximity is not performed.

The model approach shows good comparison to an analytic test case for vertical diffusion from an instantaneous surface release. Several other test cases highlight the model's ability to address more complicated problems.

The principal deficiencies in the model are directly related to assumptions in the governing convective - diffusion equation. The most severe are that the current and dispersion coefficients are assumed to be constant and that the water column is sufficiently deep so that the oil concentration approaches zero at the bottom. The lower boundary condition problem can be solved by using the method of images. The constant current and dispersion coefficients constraint can be eliminated by solving the governing equations in piece-wise vertical slices with matching boundary conditions with the upper and lower slices. While possible, this method quickly becomes more complicated and computationally intensive than a numerical finite difference or element method or a Lagrangian particle based solution to the governing equation.

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Table 1. Values of C^* determined from Delvigne and Sweeney's (1988) laboratory experiments

Oil Type	C^*
Prudhoe Bay Crude, Fresh	840 (± 200)
Prudhoe Bay Crude 10 days weathering	510 (± 130)
Ekofisk Crude Fresh	1800 (± 450)

Table 2. Field observations of dispersed oil concentrations in the water column.

Oil Spill Name and Amount	Sampling Location	Oil Type	Oil Concentration (Maximum observed)	Reference
World Prodigy 295,000 gals	Narragansett Bay, RI 0.03 m below sea surface	No. 2 Fuel Oil	4.3 ppm	Cobb et al. (1989)
Exxon Valdez 11 million gals	Prince William Sound, Alaska. At surface and 1 m below	Prudhoe Bay Crude	2 ppb (VOA) 0.7 ppb (PAH)	Neff et al. (1989)
Experimental Spill	Norwegian Coastal Waters at surface at 1 m below surface	Statfjord Crude	160 ppm 3 ppm	Lichtenthaler & Daling (1983)
Experimental Spill: 0.5 metric tons	North Sea 2 m below surface	Ekofisk Crude	3.95 ppm	Cormack & Nichols (1977)
Experimental Spill: 10-20 barrels	Long Beach, CA At sea surface under slick	Alaskan Prudhoe Bay Crude	1 ppm	McAuliffe et al. (1981)
Ekofisk Blowout	North Sea Near wellhead	Ekofisk Crude	100-400 ppb	Grabi-Nielson (1978)
Amoco Cadiz 230,000 tons	Brittany Coast throughout nearshore coastal waters	Arabian crude	200-1000 ppb	Calder & Boehm (1981)
Italc Croc Blowout 476,000 tons	Bay off Campeche Gulf of Mexico; Near wellhead, top 20 m water column	Crude	10.6 ppm	Feist and Boehm (1980)
Argo Merchant	Nantucket, MA near sea surface		450 ppb	Groose & Mattson (1977)

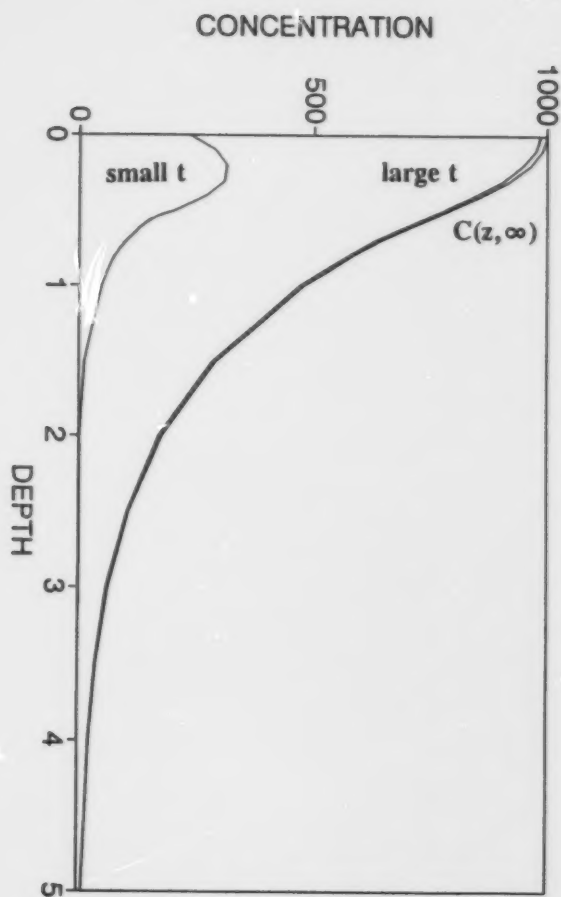


Figure 1. Model predicted vertical oil concentration profiles for small and large t .

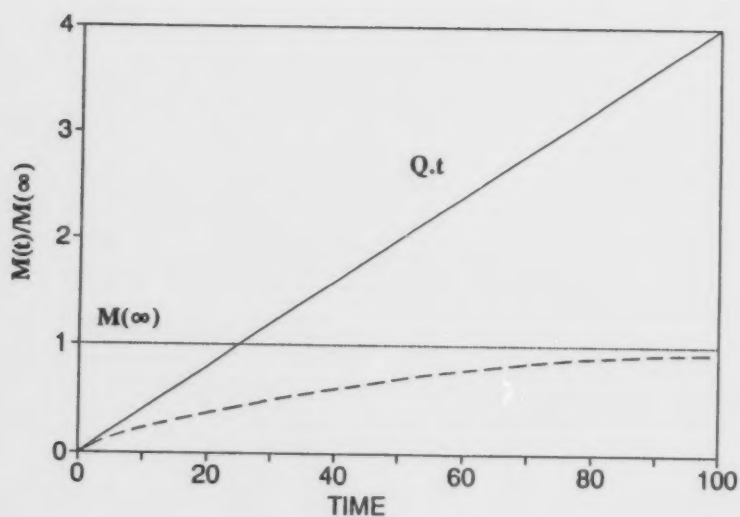


Figure 2. Entrained oil mass, $M(t)$, versus time. Solid line (-) shows the oil mass input and the dashed line (--) the total oil mass in the water column. $M(\infty)$ is the steady state oil mass in the water column.

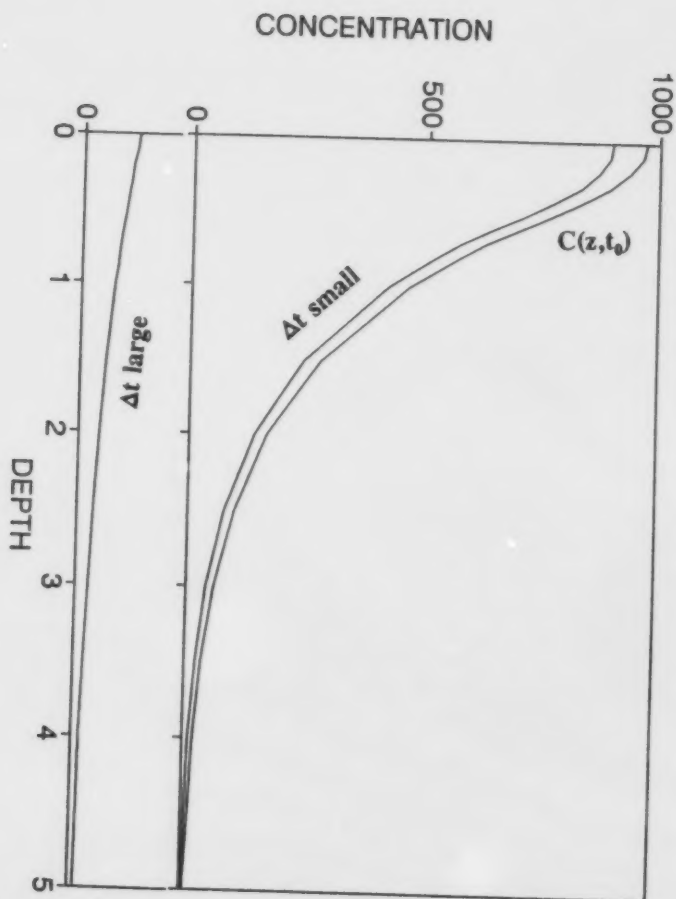


Figure 3. Model predicted vertical oil concentration profile Δt ($\Delta t = t - t_0$) time units after the oil entrainment process ceases. Concentration profiles are shown for $t = t_0$ and $t = t_0 + \Delta t$ where Δt is small and large.

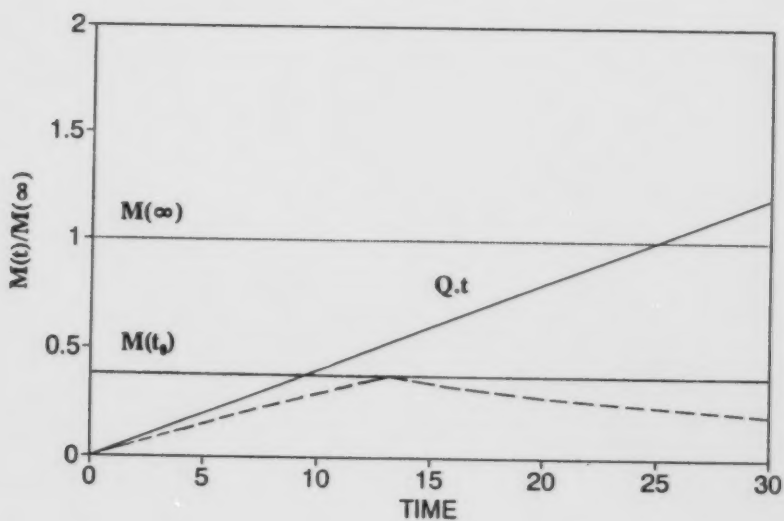


Figure 4. Entrained oil mass, $M(t)$, versus time. Solid line (-) shows the oil mass input and the dashed line (---) the total mass in the water column. $M(\infty)$ and $M(t_0)$ are the steady state oil mass in the water column for $t \rightarrow \infty$ and $t = t_0$, respectively.

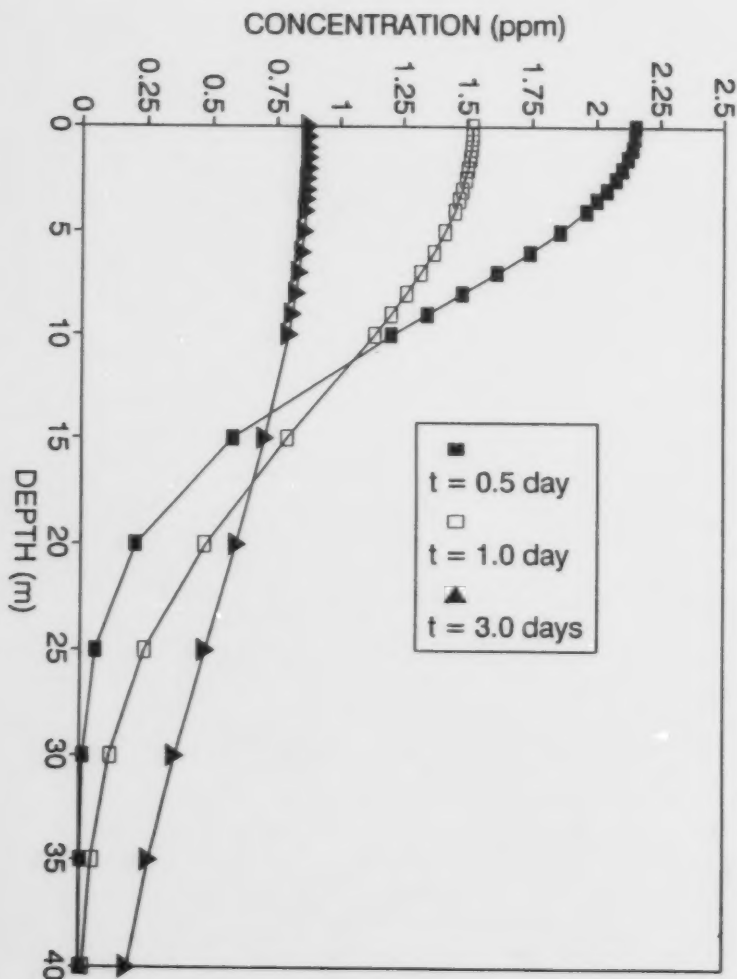


Figure 5. Comparison of analytic solution (Csanady, 1973) with the model for an instantaneous point release at the sea surface, $D = 10 \text{ cm}^2 \text{ sec}^{-1}$, no horizontal dispersion and neutrally buoyant oil droplets. Model predictions are given by the symbols and the analytic solution by the continuous lines.

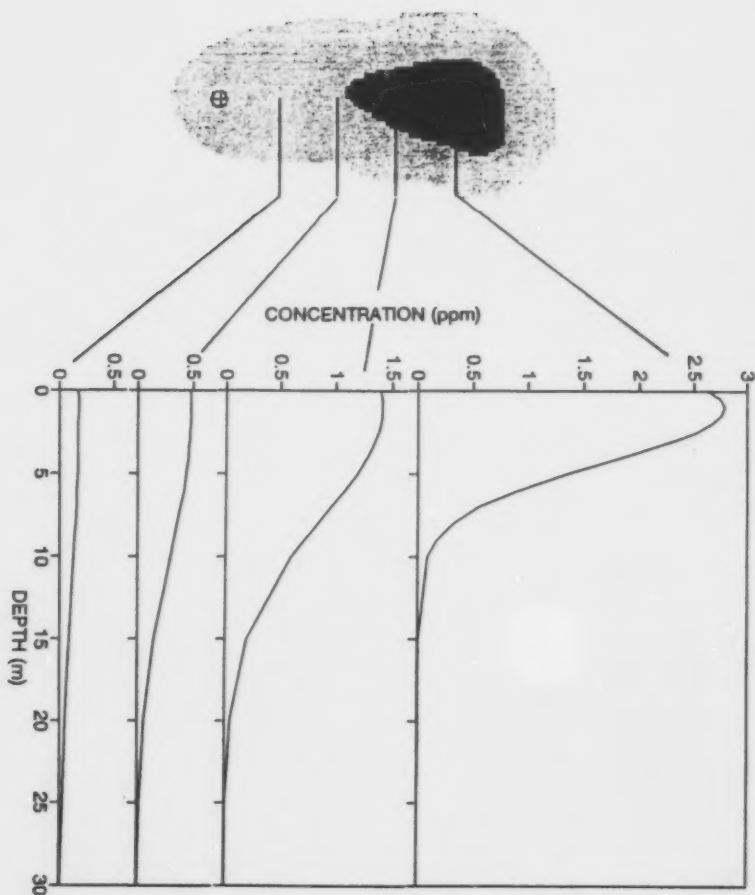


Figure 6. Plan (surface) and longitudinal-vertical section views of water column oil concentrations without resurfacing of entrained oil. Model parameters are defined in the text.

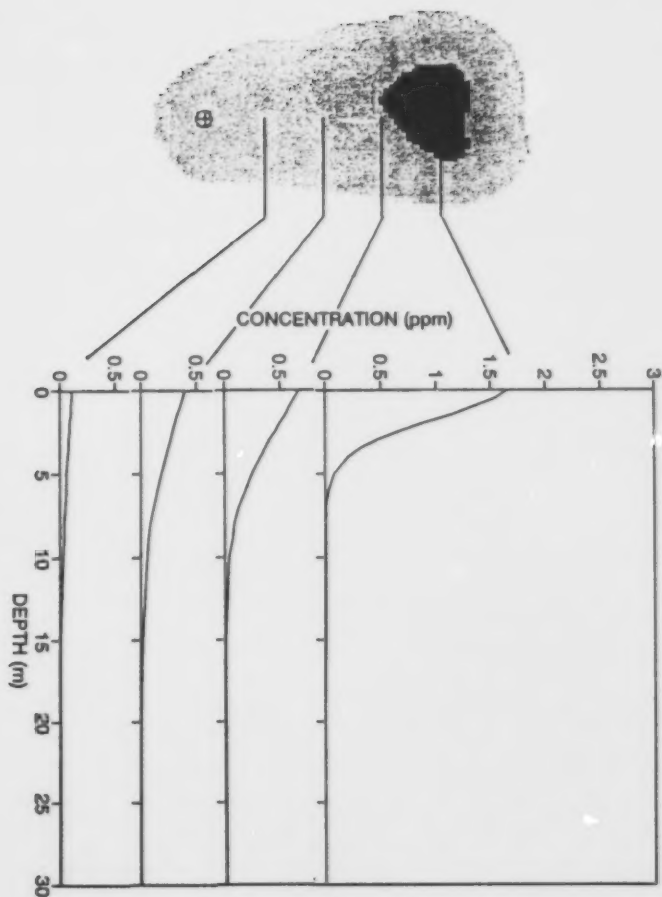


Figure 7. Plan (surface) and longitudinal-vertical section views of water column oil concentrations with resurfacing of entrained oil. Model parameters are defined in the text.

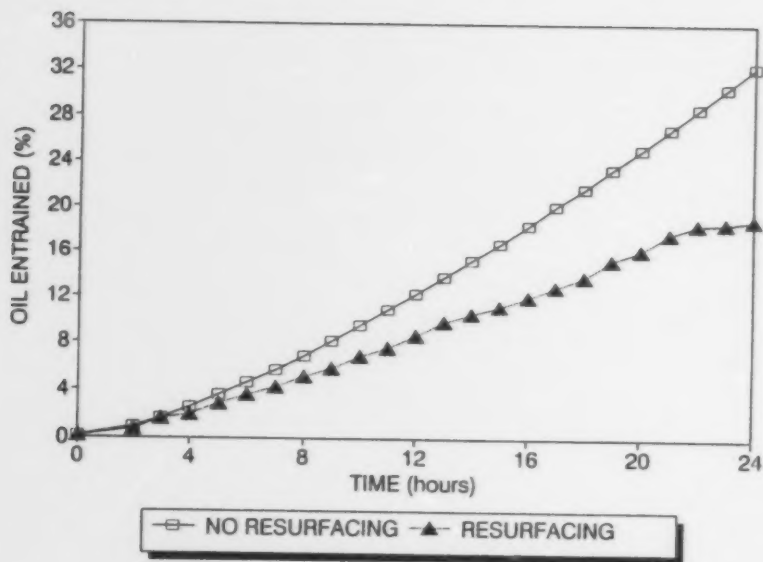


Figure 8. Percent oil mass entrainment versus time for the without and with resurfacing of entrained oil cases. Model parameters are defined in the text.

USE OF THREE GENERATIONS OF OIL SPILL MODELS DURING THE GULF WAR OIL SPILLS

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INTRODUCTION

During the Gulf War between January and May, 1991, an estimated six million barrels of oil was spilled into the Arabian Gulf. Most of the oil was spilled at or around Mina Al-Ahmadi in southern Kuwait. As part of spill-response preparatory activities in Saudi Arabia, three mathematical models, GULFSLIK I, GULFSLIK II, and OILPOL, were used to analyze the fate and transport of the spills originating at Al-Ahmadi.

The oil spill trajectory model GULFSLIK I, which is a first generation model was used as a preliminary analysis of the movements of oil spills. The trajectory model GULFSLIK II, which was used for real time predictions during the Gulf War is a second generation oil spill model. A third generation oil spill trajectory model, OILPOL, was used in operational real time to predict the surface and subsurface distribution and the fate of the spilled oil. The calculated trajectories and surface oil distributions predicted by GULFSLIK I, GULFSLIK II, and OILPOL, were then compared with sighting data. Other details concerning the use of these models during the Gulf War and their numerical basis can be found in Al-Rabeh et al. [1992].

SECTION 1: OIL SPILL MODELS

The forecasting analysis of oil spills is carried out to support real time or tactical spill response. In this study, the application three generations of oil spill trajectory and fate models were used for forecasting a series of oil spills originating off the western coast of the Arabian Gulf.

The following questions were addressed:

- where will the oil go?
- when will it get there?
- what will it look like?

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Initial trajectory estimates were made by using GULFSLIK I. Real time trajectory analysis was carried out using an oil spill trajectory model, GULFSLIK II, developed at Kuwait Fahd University of Petroleum and Minerals/Research Institute (KFUPM/RI). The trajectory analyses were used to support tactical spill response by providing the first estimates of impact areas. To further evaluate probable impacts, a third generation model, OILPOL, was used to model the effects of tidal currents and the weathering processes. This model also provided information to damage assessment studies and environmental impact analyses.

SECTION 2: BRIEF DESCRIPTION OF GULFSLIK I

The oil spill trajectory model, GULFSLIK I, is the basic trajectory model and first generation oil spill model developed during the late 1970s at KFUPM/RI. This model predicts the movements of the oil spill by considering three percent law, i.e., the center of the slick advects with a velocity equal to three percent of the wind speed. The model is best for the initial forecasting of oil spill movement. While its overall reliability is discussable, it is quite useful for rapid response. There are various versions of this first generational oil spill model available today, and GULFSLIK I strickly belongs in this category.

SECTION 3: TRAJECTORY ANALYSIS USING GULFSLIK II

GULFSLIK II is a second generation, interactive real-time model that predicts the trajectory of surface oil spills at 24-hour intervals. The model requires as input the average daily wind velocity. A database of surface currents resulting from wind speeds ranging from 5 to 35 knots at 5-knot increments in all of the eight cardinal directions is created. Surface currents for these specific wind conditions were obtained from a three-dimensional hydrodynamic model of the Gulf (Al-Rabeh et al. 1990). The surface currents resulting from any wind condition were then obtained using a standard interpolation algorithm. The mathematical basis for the model are detailed in Cekirge et al. [1989].

It is worth noting that GULFSLIK II obtains surface currents from a reliable three-dimensional hydrodynamic model of the Gulf coupled with an appropriate interpolation scheme. This is in contrast to many trajectory models that use empirical formulas. Thus, more realistic trajectory predictions can be expected as a result. GULFSLIK II, however, ignores tidal, density and thermal-driven currents. Sensitivity analysis using OILPOL clearly show that tidal currents contribute very little to net transport for periods of more than 24 hours in the Arabian Gulf. For the spills originated around Al-Ahmadi, (see Figure 1 for location), the transport of the spill due to tidal forcing only after 30 days is indicated in Figure 2. Results indicate that once surface spreading is over, no net transport is recorded over a 30 day period. It is clear however, that winds currents are mainly responsible for the net transport of the pollutant.

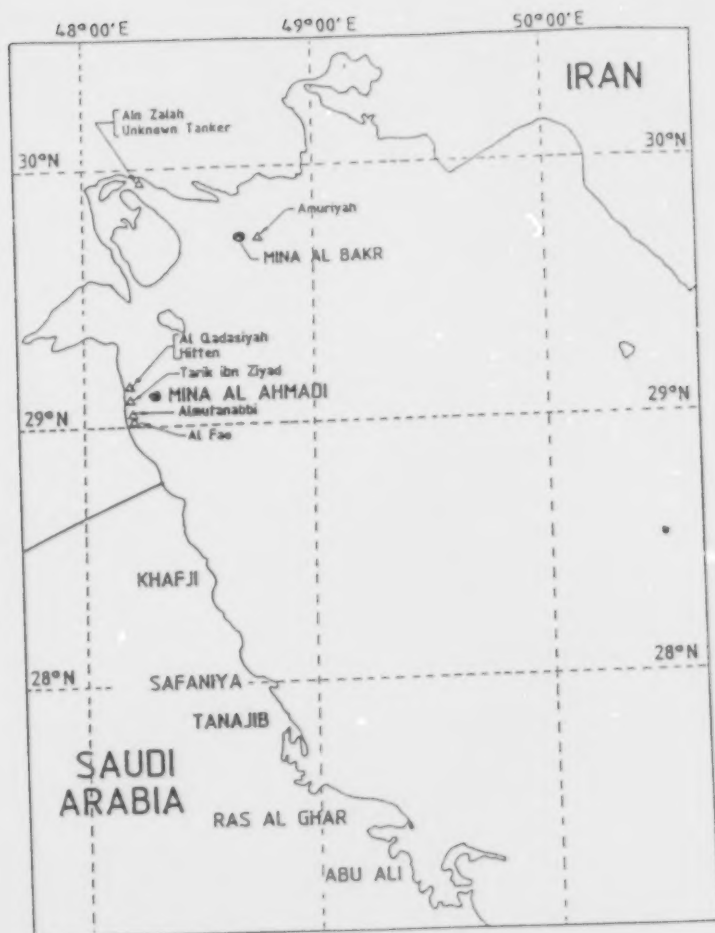


Figure 1. Regional map of the northwestern Arabian Gulf. Oil spill locations are indicated by arrows.

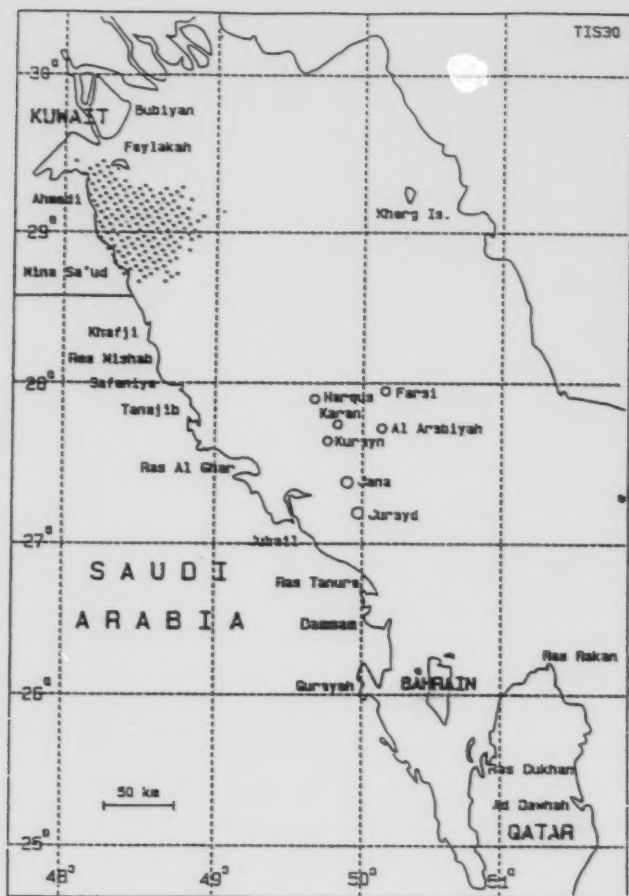


Figure 2. Surface distribution of oil due to tidal currents and surface spreading after 30 days from the start of the spill.

GULFSLIK II was used to provide short-term trajectory predictions using seven day wind forecasts. Long-term predictions were carried out using the monthly average wind velocities given in Table 1. Based on sighting data, the trajectories of spills at various locations in the western Gulf region during the months of January-April 1991 were simulated.

Table 1. Average effective monthly wind velocities.

Month	Speed (m/s)	Direction
January	5.324	141.7
February	5.487	131.7
March	5.006	132.5
April	4.483	128.5
May	4.724	118.5
June	4.892	127.7
July	3.892	122.8
August	3.000	126.3
September	3.465	132.8
October	3.296	143.4
November	4.689	147.8
December	4.784	135.9
Annual	4.471	132.7

Comparisons between predicted trajectories and actual sightings show that GULFSLIK II is reasonably accurate (Table 2, Figures 3 and 4). A sensitivity analysis indicates that accurate wind data is essential for accurate trajectory predictions.

Table 2. Comparison of actual and predicted trajectory of the leading edge of Al-Ahmadi oil spill.

Locations	Date of Oil Sighting	Predicted Date of Impact Using GULFSLIK II
KHAFJI	January 25, 1991	January 26, 1991
SAFANIYA	January 29, 1991	January 30, 1991
RAS AL GHAR	February 08, 1991	February 09, 1991
ABU ALI	February 14, 1991	February 13, 1991
RAS TANURA	March 18, 1991	March 18, 1991

The accuracy of GULFSLIK II can be further enhanced by taking a smaller directional increment in the interpolation scheme and a finer mesh in the hydrodynamic model.

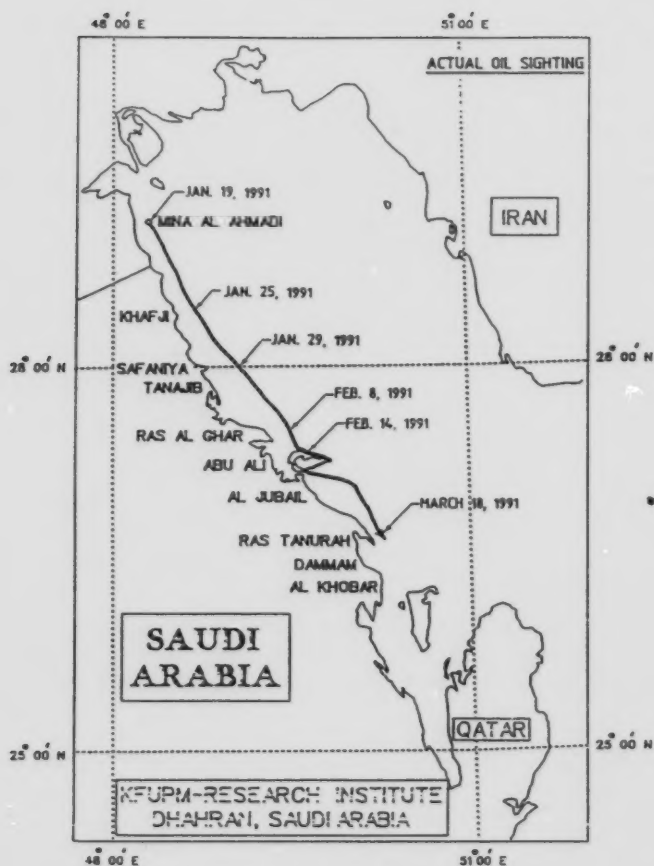


Figure 3. Actual trajectory of the oil based on overflight sightings.

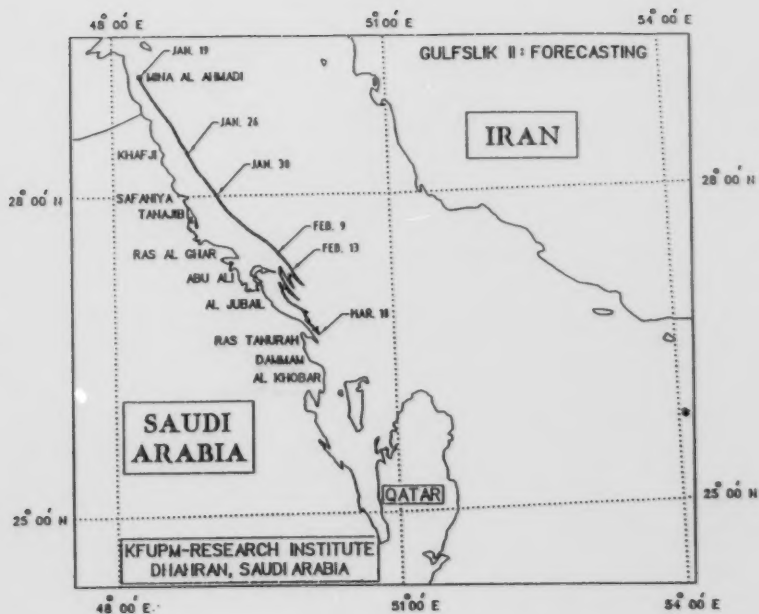


Figure 4. Predicted trajectory of the oil spill over 60 days using GULFSLIK II.

SECTION 4: THIRD GENERATION OIL SPILL MODEL, OILPOL

OILPOL is a comprehensive stochastic model that simulates the fate and transport of oil spills. The model consists of a set of algorithms describing the processes of advection, turbulent diffusion, surface spreading, vertical mechanical dispersion, emulsification, and evaporation. Each of these algorithms is developed separately and is linked to related processes and to environmental and other parameters. Details of the model are described in Al-Rabeh et al. [1989]. OILPOL requires as input the velocity field of the transporting medium. This is obtained from a three-dimensional hydrodynamic model for tidal and wind-driven currents for the region of interest. Details of the three dimensional hydrodynamic model used is described in Al-Rabeh et al. [1990].

OILPOL has been applied to analyze the transport and fate of Al-Ahmadi oil spill. A continuous spill is introduced on January 19, 1991 and stopped on January 28, 1991, at which time we know that the spill rate was reduced significantly due to allied forces bombing. An hourly spill rate of 27,390 barrels is introduced for a period of 144 hours. It is assumed that spill size is about 4,000,000 barrels, and the oil type is heavy. Wind data used in the model are provided by Saudi Aramco, MEPA, and Royal Commission for Jubail and Yanbu.

After 80 days results shows that less than 8% of the initial oil volume remain^s on the sea surface whereas, 15% is either suspended in the water column or sedimented on the sea bed. It is significant to note that due to high salinity and low energy of the Arabian Gulf, less oil is expected to enter the water column as compared with less saline and more energetic seas such as the North Sea. Most of the oil, approximately 45% of the initial volume, has impacted the coastal region from Latitude 28°44' to 27°10'. More than one-third of the oil has evaporated. It is worth noting that a very small fraction of crude oil dissolves into the water columns, typically less than 1% of the total volume, but nevertheless can be significant environmentally.

Surface oil distribution as predicted by OILPOL is compared with sighting data which was compiled from ground and aerial observations, the Side Looking Air-Born Radar (SLAR) operated by the U.S. Coast Guard, and satellite imagery (compare Figures 5 and 6). The subsurface distribution of oil is presented by Figure 7, which is most important application of third generation of oil spill models. The results show excellent agreement between model results and actual sightings. The continuing work on OILPOL is also extended to include the impact of the refloating of beached oil. A finer mesh is also being developed in order to better represent certain coastal areas.



Figure 5. Surface distribution of oil after 30 days from the start of the spill.

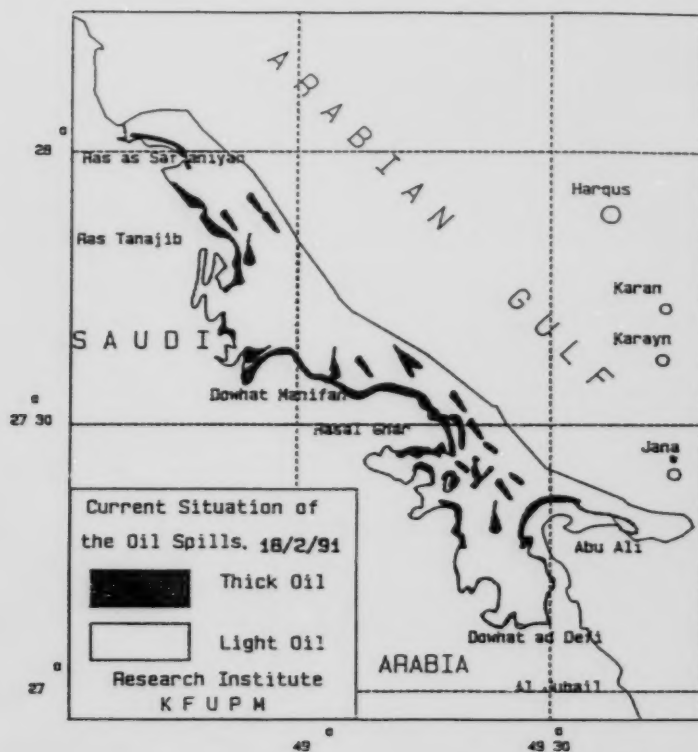


Figure 6. Actual oil spill distribution on Feb. 18, 1991. (No data available north of Safaniya).

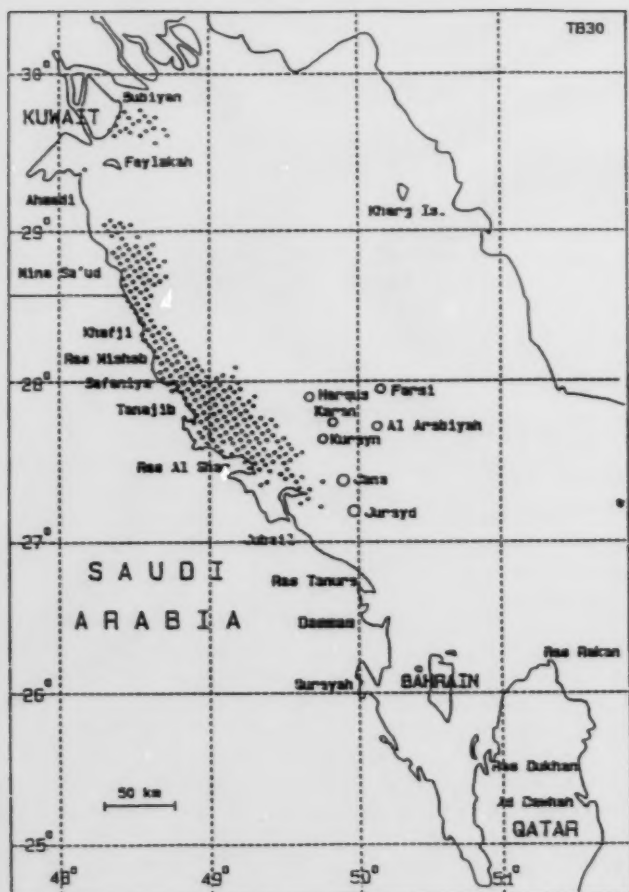


Figure 7. Subsurface distribution of oil after 30 days from the start of the spill.

SECTION 5: CONCLUSIONS

Real time trajectory analysis of the Gulf War oil spills was carried out using an oil spill trajectory model, GULFSLIK II. The trajectory analysis was used to support tactical spill response. A three-dimensional fate and transport analysis was carried out using OILPOL to support damage assessment studies and environmental impact evaluations.

GULFSLIK II was used in an operational mode to predict the trajectories of surface oil spills at various locations off the coast of Kuwait and Saudi Arabia. Short-term predictions were made using 7-day wind forecasts. Long-term predictions were made using monthly wind averages. Comparisons between predicted trajectories and actual sightings show that GULFSLIK II is reasonably accurate. However, the accuracy of GULFSLIK II can be further enhanced by taking a smaller directional increment in the interpolation scheme and a finer mesh in the hydrodynamic model.

OILPOL is used to provide three-dimensional transport and fate analysis of spill from Al-Ahmadi. After 80 days results show that less than 8% of the initial oil volume remains on the sea surface whereas, 15% is either suspended in the water column or sedimented on the sea bed. Most of the oil, approximately 45% of the initial volume, has impacted the coastal region from latitude $28^{\circ} 44'$ to $27^{\circ} 10'$. More than one third of the oil has evaporated. Comparisons of simulation results with actual sighting data show excellent agreement.

Acknowledgements

The oil spill models discussed in this paper were applied by KFUPM/RI during the Gulf War spills under the sponsorship of the Meteorology and Environmental Protection Agency (MEPA) of Saudi Arabia. Additional details are presented in Al-Rabeh et al. [1991]. MEPA, Saudi Aramco, the Royal Commission for Jubail and Yanbu, the Civil Defense of Saudi Arabia, The US Coast Guard, and the US National Oceanic and Atmospheric Administration provided data and necessary help for this work. The principal author (H.M. Cekirge) thanks Dr. Erich R. Gundlach for his encouragement to publish this summary of the three primary oil spill models used in Saudi Arabia during the Gulf War spills.

SECTION 6: REFERENCES

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AERIAL SPRAYING OF DEMULSIFIERS TO ENHANCE THE NATURAL DISPERSION OF OIL SLICKS

by

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1. INTRODUCTION

Most oils spilt at sea form water-in-oil emulsions. Emulsion formation increases both the volume of pollutant, its viscosity and its persistence on the sea surface. At-sea recovery of oil or emulsion is potentially an attractive option because it totally removes some of the pollutant from the marine environment. However, for many oil spill incidents, at-sea recovery alone may be impractical or impossible. The UK has a relatively long coastline which can be accessed fairly rapidly by aircraft whilst the surrounding shelf seas are rarely flat calm, are generally well-mixed vertically and have short flushing times. These conditions make the aerial application of dispersants particularly appropriate and dispersant use is the primary UK countermeasure for oil spills at sea. Other countries have a mixed attitude to dispersant spraying. Unfortunately, dispersants tend to become ineffective once oils have become emulsified, there is often only a short period when dispersants may be used with best confidence and effect.

Meso-scale tests carried out by WSL in 1989 evaluated the effectiveness of demulsifiers both in inhibiting emulsion formation and breaking emulsions once formed on the sea surface. These effects may sustain or enhance the rate of natural dispersion. Although the 1989 trials did not secure totally unambiguous quantitative data, the evidence obtained indicated that demulsifier solution sprayed at very low application rates onto oil slicks was successful in increasing spreading and inhibiting emulsification.

This paper describes larger scale sea trials carried out to investigate the effectiveness of the aerial application of demulsifiers and its potential as an oil spill response tool.

2. TEST PROGRAMME

2.1 Preliminary Testing of Demulsifier Solution

Early work by Lee, 1980, had tested several demulsifiers at different application rates, temperatures and mixing regimes on various high viscosity water-in-oil emulsions. These experiments indicated that the demulsifiers available at that time were oil specific ie typically they worked well with some crude oil emulsions but not with others. Bridle et al, 1980, Bulst and Ross, 1987 and subsequent laboratory testwork at Warren Spring Laboratory suggested that the Shell demulsifier LA 1834 could be effective over a broad spectrum of oil types and it was therefore selected for evaluation at sea.

Unfortunately LA 1834 has a higher viscosity than can be readily accommodated by existing aerial spraying equipment and several solvents were examined which could potentially reduce the viscosity of the solution to an acceptable level. The solvent was required to fulfil various criteria in addition to viscosity change:

- i) to have no (or little) effect on the performance of the demulsifier;
- ii) to have low marine toxicity (LA 1834 itself has passed toxicity test criteria set by the UK Government's Ministry of Agriculture, Fisheries and Food);
- iii) to be safe to handle when loading aircraft, etc;
- iv) to have a flash point greater than 60°C (the safe limit set by the UK's Civil Aviation Authority).

The flash point criterion ruled out all but one of the solvents considered (Shellsol T, Shellsol AB and Isopar M have flash points of 60, 63 and 78°C, respectively, which were considered to be too close to the 60°C safe limit) and, as a result, laboratory tests were carried out only with Shell Surdyne X113 (flash point 123°C). X113 is practically non-toxic to fish and aquatic invertebrates, is inherently biodegradable and has a low order of acute toxicity. In addition, it is immiscible with water and of low density and the contact time between the demulsifier solution and the oil/emulsion should therefore be prolonged.

2.1.1 Effectiveness Testing of Demulsifier Solutions

A small number of tests were carried out to identify whether there were any adverse effects of solvent dilution on the demulsifier performance. Beakers were set up each containing 500 ml seawater and 100 ml of Medium Fuel Oil/Gas Oil (MFO/GO) emulsion (60% water). The beakers were left for 24 hours before treatment to allow the emulsion to settle to an even layer on the seawater surface. Demulsifier solutions from 10% to 90% LA 1834 were added to give LA 1834:emulsion ratios from 1:2000 to 1:200.

No energy was applied to the set of beakers for the first 2 hours of the experiment, after which time each beaker was gently shaken in the same manner at approximately 2 hour intervals. Initial observations showed there to be no detectable difference in the effects of the different concentrations of demulsifier on the sample emulsions. Each treatment successfully demulsified the thin surface film of emulsion over a similar time period. After shaking, each emulsion sample was observed to break at a similar rate, ie visual observation detected no discernable difference between the beakers. All emulsion samples had reverted to black oil and water after a 24 hour period. In the light of these results, no further tests of effectiveness were felt to be necessary at this time.

2.1.2 Viscosity Measurement of Demulsifier Solutions

To achieve a viscosity operationally compatible with the spray system aboard the Britten Norman Islander aircraft, a series of viscosity measurements were made on a range of demulsifier solutions at a range of temperatures. The demulsifier LA 1834 is relatively highly viscous at low temperatures; at 0°C = 6000 mPas and even at 20°C its viscosity remains about 1100 cP. From the outset of this work it was determined that the viscosity of the demulsifier solution should be <200 cP or less at temperatures approaching 0°C.

This specification is similar to that for dispersants and thus eliminated the need for detailed and costly spray distribution trials.

Figure 1 gives measured viscosity against a range of demulsifier:solvent ratios at 6°C. At this temperature an operationally practical viscosity of ~200 cP is achieved at ~55% LA 1834. (The demulsifier solution is near-Newtonian over the range of shear rates tested and experienced operationally during spraying). Figure 2 illustrates the effect of temperature on an equi-volume mixture of demulsifier and solvent; it is this ratio which was used throughout the sea trials. Viscosity measurements were made at WSL using a Contraves Rheomat 30 viscometer.

2.1.3 Spray Testing at Coventry Airport

Spray runs were carried out at Coventry Airport in advance of the sea trials to determine approximately the potential range of swath widths and discharge rates of the Islander spray system. Achieving an appropriate pre-determined dose-ratio of demulsifier:oil using a test slick at sea is difficult. The variables associated with the application system dose rate are primarily the discharge rate, swath width (including droplet size and distribution in the swath) and the aircraft speed. Those variables associated with the slick to be treated are essentially the surface area, the variation in thickness within the area and, to some extent, the shape and orientation of the test slick.

Work was carried out therefore to determine the range of application rates which could be achieved without any major modification to the spray system. As the tests were to be carried out over land it was decided to use a premixed Carboxymethylcellulose solution (CMC). CMC is both non-toxic and is near-Newtonian over a shear rate range from 50 to 700 s^{-1} thus enabling the close determination of flow rates and swath widths of a liquid similar in viscosity to the demulsifier solution to be used in the sea trials.

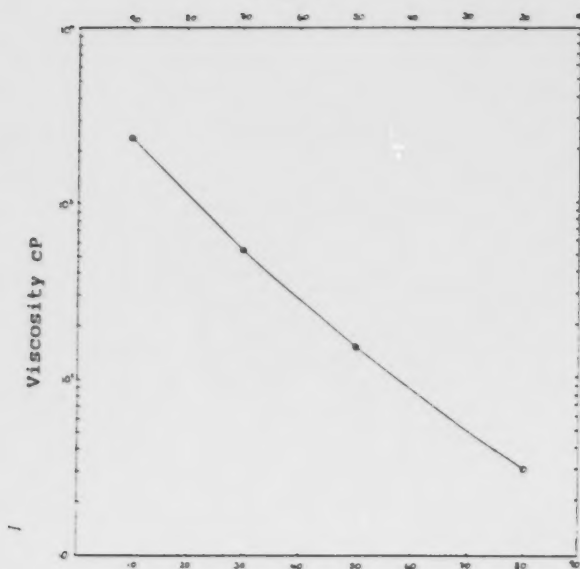
To achieve a best estimate of the swath distribution a row of white PVC collection trays was laid across the flight path. A total of 16 trays, each approximately 0.6 m square, were laid out to give an array width of 20 m aligned at 90° to the prevailing wind. Traffic cones were set up both to mark the edge of the array and to assist the pilot in lining up of the flight path.

The aircraft was loaded with 200 l of dyed CMC solution prior to each test flight. The discharge rate was calculated from the volume of CMC solution used and the precise timing of each spray run. The swath width and approximate droplet size distribution was determined by taking photographs of the individually labelled PVC trays. Minor modifications to the spray boom were made to achieve the desired discharge rate of between 3 and 4 $l s^{-1}$. This involved simply blanking off some of the nozzle orifices in order to reduce the discharge rate.

Each test flight aimed to determine 1) the flow rate of CMC solution, 2) the swath width and 3) the approximate droplet size distribution across the swath.

- 1) Flow rate- The desired flow rate of 3-4 $l s^{-1}$ was readily achieved within three preliminary spray runs. This was achieved by blanking off six of the nozzle orifices out of 23 on each of the two booms.

LA1834



Surdyne X113

FIGURE 1. Viscosity of LA1834/Surdyne X113 Solutions at 6°C

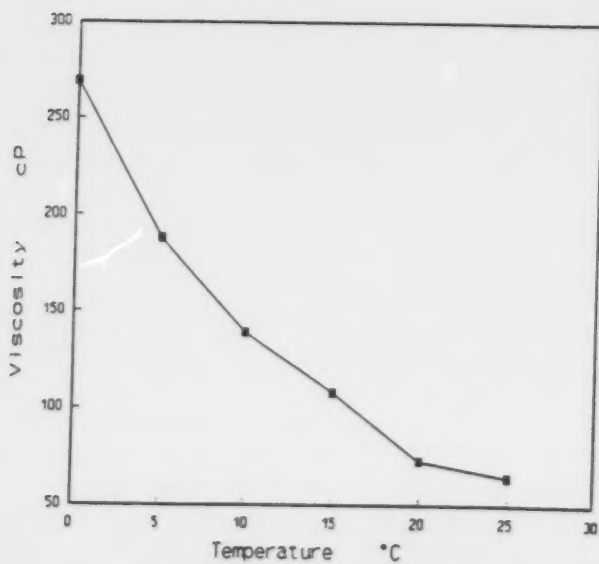


FIGURE 2. Viscosity of LA1834/Surdyne vs Temperature

- 2) Swath width - The swath width over three dyed CMC solution spray runs was consistently between 11 and 15 m, showing a strong central peak in both deposition rate and droplet size. From visual examination of the swath test array post spraying and later in photographs, it is estimated that approximately 60-70% deposition occurred in the centre 5 m sector of the swath.
- 3) Droplet size distribution - The estimated peak droplet size diameter in the swath centre was $\sim 1000 \mu\text{m}$ decreasing to $\sim 120 \mu\text{m}$ at the swath margin. The observed droplet sizes for CMC solution and demulsifier solution were similar to typical values for dispersants. The optimum droplet size for dispersants is regarded as between 500 and 700 μm for application to oil (The Institute of Petroleum, 1986).

2.2 Sea Trials

A series of four trials was carried out in an area of the Southern North Sea where Warren Spring Laboratory has a licence to discharge oil and chemicals for experimental purposes. A MFO/GO mix was used in two of the trials to simulate weathered but not emulsified oil; a crude oil was used in the third trial; a MFO/GO emulsion containing 54% water was used in the fourth trial.

Each sea trial involved the discharge of two test slicks, one a control and the other to be treated with demulsifier solution. To minimise any risk of one slick being wind driven towards another in any one trial, the slicks were laid across the prevailing wind at a minimum of 1.5 nautical miles apart. In an effort to ease synchrony with the spray aircraft and maximise the possible daylight surface sampling time of the test slicks, the control slick was always laid first. Three slicks were laid in Trial 3 with a view to spraying one straight after discharge and one later when the oil had weathered and emulsified naturally; unfavourable weather conditions thwarted the second part of the experiment.

Remote sensing imagery was obtained from all four trials using the infrared (IR) and ultraviolet (UV) instruments on the Cessna 404 used by the UK Government. Surface samples were collected where possible for subsequent analysis. The discharges are summarised in Table 1.

2.2.1 Aerial Application of Demulsifier Solution

Achieving a specified dose ratio of demulsifier:oil whilst maintaining an even application over the entire test slicks was not easy because of the difficulties of predicting or controlling some of the main variables, particularly the initial spreading of the slicks. Nevertheless, various estimates and assumptions were made in an attempt to spray within the desired demulsifier:oil ratio range of between 1:100 and 1:400. The swath width was assumed to be approximately 13.5 m; the oil/emulsion to be treated was assumed to have spread to an average thickness of approximately 0.5 mm at the time when the aircraft began spraying. Lateral drift of the swath was minimised by flying the aircraft into the wind when spraying. The spray data are summarised in Table 2.

TABLE 1. - Summary of 1991 Sea Trials

Trial Date	1 11 June			2 23-24 July			3 13-14 August				4 18 September		
	MFO/GO		T	MFO/GO		T	Forties blend crude		C _w	C _E	T	MFO/GO Emulsion	
Oil type/Volume (m ³)	10.2		9.9	14.7		18.3			15.0	16.0	14.0	26.5	
Discharge time (GMT)	C = 1020, T = 1100			C = 0730, T = 0820			C _E = 0820, C _w = 0910, T = 1000					C = 0700, T = 0800	
Age of oil when treated	10 mins			10 mins			c 15 mins					55 mins	
Surface sampling duration (Control) (Hrs)	8.7			31.7			32.0					9.7	
Surface sampling duration (Treated) (Hrs)	1.3			9.8			10.0					4.7	

C = Control, C_E = Control Slick East, C_w = Control Slick West, T = Treated

TABLE 2. - Summary of Spray Data

Trial	Original Oil Volume of Control (m ³)	Original Oil Volume of Treated (m ³)	Total Demulsifier Solution Sprayed (litre)	Demulsifier Solution Spray Rate (litre s ⁻¹)	Spray Time (Impacting Slick) (s)	Dose Ratio (Demulsifier:Oil)
1. MFO/GO 50%/50%	10.2	9.9	96.5	4.04	24	1:207
2. MFO/GO 50%/50%	14.7	18.3	212.3	7.15	30	1:172
3. Forties Crude Oil	14.0	16.0	406.3	6.83	59	1:74
4. MFO/GO Emulsion	12.7	13.1	465.0	6.20	75	1:56

Demulsifier solution = 50% LA 1834 and 50% Surdyne X113

Demulsifier alone is used to calculate dose ratio

Total volume of emulsion = 24.8 m³ (control) Total volume of emulsion = 28.5 m³ (treated).
Composed of 54% sea water.

The final mean dose ratios are calculated from the known flow rate and an estimation of the percentage contact of each spray run with the target oil. One example of IR imagery from Trial 3 which clearly illustrates the coverage of the treated slick is shown in Figure 3. The darker trails distinguish the demulsifier solution deposition whilst the light (white) patches show the thicker patches of oil. The imagery suggests that the supervising aircrew estimate of over 80% of the demulsifier solution contacting the oil may be optimistic. A possibly more realistic estimate of 60% would reduce the overall demulsifier:oil ratio from 1:74 to 1:108. It must be emphasised, however, that both the aircrew estimate and the imagery interpretation contain a subjective element.

During Trial 2, weather conditions were sufficiently calm to attempt an evaluation at sea of the swath characteristics, on this occasion using demulsifier solution. A test array of ten trays was set up on a 12 m ladder projecting from the bow of the small work boat, Black Tern; Figure 5 shows a schematic diagram of the array construction. As the demulsifier solution used in the trials did not contain marker dye, absorbent blotting paper was placed in each tray to detect the pattern of demulsifier solution depositions. The first Islander overflight was successful in spraying almost over the centre of the array at a height of approximately 8 m. The results confirmed the findings at Coventry Airport in that approximately 60-70% of the deposition occurred in the centre 5 m of the swath and the swath width was between 11 and 15 m. No data on droplet size could be obtained from this experiment.

2.2.2 Slick Dimensions

Previous testwork had indicated that demulsifiers work by increasing slick spreading and thus enhancing the overall rate of natural dispersion. Treated slicks could therefore be expected to increase in area more rapidly than the control slicks and then disperse more rapidly. Remote sensing data provided the means to attempt to quantify these phenomena.

IR, UV and video data were obtained during all four sea trials with emphasis given to direct comparisons between the control and treated slicks at a similar age. Particular importance was attached to study of 1) Initial slick spreading and measurement of overall slick dimensions; 2) the areas of thick oil/emulsion; and 3) the longevity of the slicks. Adverse weather conditions such as low cloud sometimes affected the quality of data obtained.

- 1) Slick spreading and dimensions - Figure 4 shows slick areas vs time for the trials. In Trials 1 and 2 the treated slick spread quickly to a greater peak area than the control slick and, in both cases, when the treated slicks could barely be detected by the aircraft instruments the control slick continued to give a strong IR return. Calm weather complicated Trial 3 as it resulted in all three slicks spreading more than normal. Visual observations after approximately 30 hours indicated that the treated slick was noticeably more widely spread than the controls. In Trial 4, the treated emulsion had largely demulsified after 7 hours and after 25 hours it gave only weak returns on IR and SLAR sensors whereas the control slick covered a large area and gave strong returns.
- 2) Areas of thick oil/emulsion - Figure 5 shows that the area of thick oil in the treated slicks consistently diminished much more rapidly than the control slicks. The imagery in Figure 6 illustrates the more uniform



FIGURE 3. IR Image of Treated Slick Immediately After Spraying (Trial 3)

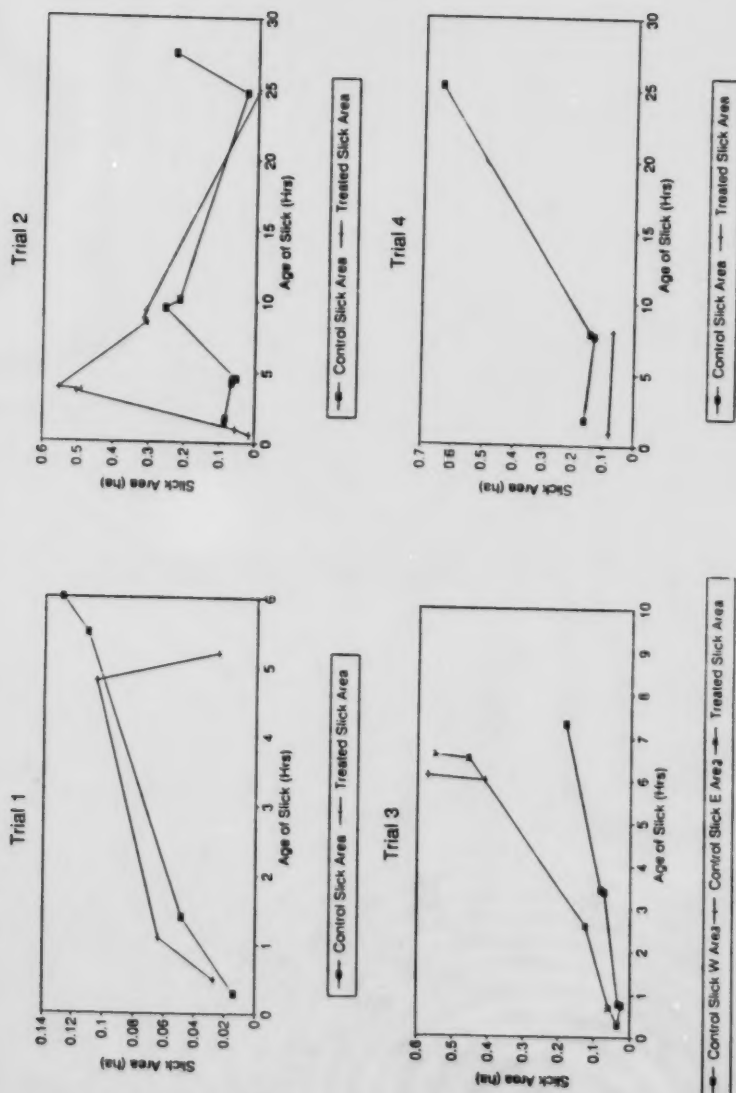


FIGURE 4. Sick Areas

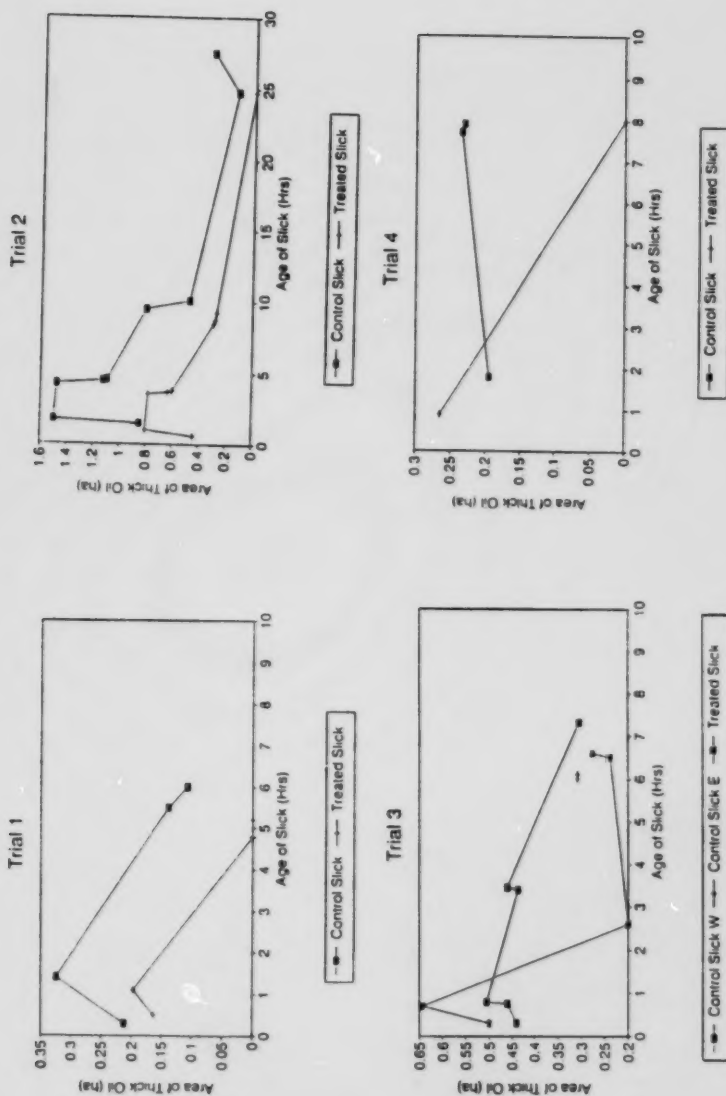


FIGURE 5. Areas of Thick Oil



FIGURE 6a. IR Image of Treated Slick 9 Hours After Discharge (Trial 2)



FIGURE 6b. IR Image of Control Slick 9 Hours After Discharge (Trial 2)

appearance of the treated slick with much less thick oil as indicated by the light patches.

- 3) Longevity - In Trials 1 and 2 the treated slicks had disappeared whilst the control slicks were still of significant size and containing thick patches of oil. After 48 hours of Trial 3 only two slicks could be found, the available evidence indicating that the treated slick had completely dispersed. The area of thick oil remaining in the Trial 4 control slick at the time of disappearance of the treated slick suggested that the control slick would probably have persisted many times longer than the treated slick.

2.2.3 Surface Sampling

The at-sea monitoring of the experimental slicks involved visual observation and surface sampling of the slicks for subsequent viscometry and water content analysis. In all trials the treated slick was monitored by the mother ship, R V Seaspring and the control slick was monitored by the work boat, Black Tern. Surface samples were collected by concentrating oil against the side of the vessel as it drifted slowly into the oil and the use of the larger ship with the treated slick gave a greater chance of obtaining sufficient oil to sample from the thin films. The samples of oil/emulsion were immediately transferred into a separating funnel to remove any free sea water and stored in a sealed kilner jar. Viscosity measurements were made at sea as soon as possible after sample collection; water content analyses were made on return to WSL.

- 1) Viscosity of Surface Samples - Monitoring of the changing viscosity of the experimental slicks by the measurement of surface samples proved to be difficult for a number of reasons. Firstly, sampling of the treated slick in Trials 1 and 4 proved to be extremely difficult after a few hours when insufficient thick oil could be collected against the side of RV Seaspring to permit sampling of sufficient oil or emulsion. This problem arose due to the rapid spreading of the treated oil or emulsion. Secondly there were logistical and technical problems in making measurements at sea. Throughout the four sea trials there were occasional difficulties in making viscosity measurements early enough to be meaningful. In particular, some newly-formed emulsions were found to be unstable, where separation of the oil and water phases began to take place even before viscosity measurements could be made. During the second sea trial, several problems associated with unstable emulsion samples and instrument failure made it impossible to collect meaningful viscosity data.

The data that could be obtained typically showed higher viscosities from the control slicks than the treated slicks.

- 2) Water Content of Surface Samples - Water content analysis was carried out for samples on which viscosity measurements had been made, excepting Trial 2 when instrument failure prevented the measurement of sample viscosities. At the time of analysis the majority of samples had partly separated to the oil and water phases. For those samples which had separated, the water phase was drained off and measured, the remaining oil/water emulsion being homogenised prior to sub sampling and water content analysis. Determination of emulsion water content

was made by the Dean and Stark method (The Institute of Petroleum, 1983).

In general the control slicks showed a greater tendency to take up and retain water than the treated slicks, confirming their greater persistence.

An exception to this were the relatively high water contents measured in samples from the treated slick between age 4 and 9 hours in Trial 3. This may reflect the incomplete initial coverage of the slick with demulsifier solution leaving a patch of untreated oil which could be readily sampled.

3. DISCUSSION

The work has demonstrated the potential of demulsifiers to treat effectively oil spilt at sea. The four sea trials have shown that the application of demulsifier solution has hastened the natural dispersion of both fresh and emulsified oil to a greater degree than the adjacent control slicks. The practical sea-trials approach to this work proved necessary to arrive at a near-operational system within a fairly short time scale. Although this approach presented a number of practical and logistical problems, the sea trials proved successful in both effecting the co-ordination of aircraft, surface vessels and personnel, and in generating a comprehensive data set.

Demulsifier solution viscosity varies according to the ambient air temperature; this in turn will affect both the flow rate of the demulsifier solution and droplet size distribution. In the case of the products tested in this work the required viscosity may be achieved by altering the relative concentrations of demulsifier and solvent.

The target range of flow rates for the Islander spraying system of between 3 and 6 l s⁻¹ was easily achieved. Assuming an aircraft speed of 50 m s⁻¹, a swath width of 15 m and a flow rate of 6 l s⁻¹, the mean demulsifier solution:oil dose ratios theoretically achieved are 1:125 for a 1 mm mean thickness of oil and 1:1250 for a 10 mm thickness of oil. Theoretically at least, flow rates of between 3 and 6 l s⁻¹ produce workable demulsifier:oil dose ratios for oil thicknesses in the range 2-8 mm. The current Islander spraying system has two further mechanisms to reduce the flow rate from the spray boom. Firstly, additional blanks can be installed into nozzle orifices to restrict flow and secondly the fan powering the centrifugal pump may be feathered to reduce its power and therefore the demulsifier solution flowrate. In any case, it is likely that the operational use of demulsifiers would concentrate on treating the thicker patches of oil.

In the UK, the larger DC3 aircraft are currently used for dispersant spraying and would probably be required to be modified to spray demulsifier solution if demulsifiers are to be incorporated into the Marine Pollution Control Unit's response strategy. The details of such modifications have not yet been considered. It is also not yet clear how dispersants and demulsifiers interact and precisely what role each chemical would fulfil. Nevertheless, demulsifiers open up the possibility of dealing with oil spills at sea by aerial spraying over a much longer time window than has previously been possible with dispersants.

4. CONCLUSIONS

The demulsifier solution used in this work proved extremely effective in enhancing spreading, reducing viscosity and ultimately resulting in the accelerated dispersion of oil and emulsion in treated experimental oil slicks. It appeared to remain with the treated slicks after aerial application, influencing slick behaviour for a considerable time.

Comprehensive slick coverage at appropriate low dose ratios, particularly over areas of thick oil, is possible with the current Islander spray system provided direction by a reconnaissance aircraft is available. Further work is needed to convert the larger DC3 aircraft for demulsifier spraying.

Demulsifiers therefore appear an attractive additional oil spill response weapon, effective both in inhibiting emulsion formation thus enhancing natural dispersion and also in breaking emulsions already formed. However, various aspects of their use require further investigation. In particular, a more detailed study is needed of the main factors affecting their performance with a range of oils and emulsions including their interaction with dispersants. Demulsifiers have been shown to be effective at much lower dose ratios than dispersants but the minimum has not been clearly established. No laboratory test protocol exists for assessing the efficiency of demulsifiers. Despite these omissions, a system will be in place to enable demulsifier solution to be tested operationally in the UK in the very near future.

5. ACKNOWLEDGEMENTS

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LABORATORY TESTING OF DISPERSANTS
UNDER ARCTIC CONDITIONS

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ABSTRACT

The effectiveness of relevant dispersants for use under "arctic conditions" have been tested with the IFP dilution test. "Arctic conditions" in this context are defined as low temperature (0°C) and water salinities of 0.5‰ and 3.3‰. The study was performed in two steps with first a screening activity where 14 dispersants were tested on water-in-oil (w/o) emulsions from two weathered oil types. In the next step the five most promising dispersants were tested on both weathered water free oils and w/o emulsions from four different oil types.

The results from this study shows that many of the most used dispersants which previously have shown an excellent effectiveness at high salinity (3.3‰) may give a very low effectiveness at low salinity conditions (0.5‰). Recently developed products especially designed for low salinity use (e.g. Inipol IPF) are effective at low salinities, but suffer from a rather poor effectiveness at higher salinities. This is of significant operational importance in arctic oil spill combat operations since the salinity may vary due to ice melting.

This study of dispersant effectiveness under arctic conditions shows the need for development of dispersants with high effectiveness both at low temperature (0°C) and over a wide range of salinities (3.3‰ to 0.5‰).

INTRODUCTION

Since the Torrey Canyon accident more than 20 years ago, extensive studies have been carried out in order to assess the effectiveness and biological effects of using dispersants in oil spill combat operations (e.g. NRC, 1989). As a result of these research activities, the use of dispersants have got increasingly favourable attention in many countries during the past years. This is due to the manufacturing of less toxic dispersants, better application techniques and better knowledge of the biological effects of dispersants and chemically dispersed oil. The limitations for the use of existing mechanical equipment (booms and

¹ New name from May 5. 1992. Former name: Continental Shelf and petroleum Technology Research Institute

skimmers) have also become more clearly defined during recent years.

From an operational point of view it is essential to identify the types of dispersant products which will show the best response to the different groups of oils, and under various environmental conditions. Although much progress has been made during the past 10 years, further research is needed in optimizing the effectiveness of dispersants under different oil spill situations. One aim of the previous research at IKU-SINTEF has been to map the chemical dispersability of different North Sea crudes at various degrees of weathering at typical North Sea environmental conditions.

As oil exploration moves further north on the Norwegian continental shelf, the questions concerning the efficiency of oil spill contingency under arctic conditions become more important. The results presented in this paper are from the first phase of a research project where one of the aims is to test existing and develop new dispersants with higher effectiveness under arctic conditions. "Arctic laboratory conditions" in this context are defined as low temperature (0°C) and sea water salinity between 0.5‰ and 3.3‰.

The main part of the existing commercial available dispersants have been formulated and tested for use at temperate seawater (sea temperature above 10°C and salinities around 3.3‰). Preliminary studies indicate that many of these products may fail at low temperatures and also at low salinity (Byford et al., 1983, Lehtinen and Vasala, 1984, Bocard and Castaing, 1986, Daling et al., 1991).

Research performed during the last years at IKU-SINTEF and at other research institutions (e.g. ELF in France and BP in UK) has shown a large potential for optimization of dispersants. This is particularly relevant for customizing dispersants for different oil types or specific environmental conditions e.g. arctic conditions; low temperatures and low salinities.

This study represents a laboratory screening of the effectiveness of 14 commercial dispersants. Results from more extensive testing of the five most promising dispersants with the highest effectiveness from the screening test are also given.

EXPERIMENTAL CONDITIONS

Effectiveness testing

The effectiveness of the dispersants were tested in the laboratory with the IFP dilution test (Bocard et al., 1984). Further details concerning this dispersant effectiveness test method are described by Daling et al. 1990. The effectiveness from the IFP-test shows the different dispersants relative ability to disperse an oil into the water column. The test conditions for the IFP-test in this study were: Dispersant to oil or dispersant to w/o-emulsion ratio: 1:25, temperature: 0°C and sea water salinity: 3.3 and 0.5 ‰. These salinities were selected because 0.5‰ and 3.3‰ are expected to be the extreme values for surface

waters in arctic areas.

Oil Viscosity measurement

The viscosity of the oils and the w/o-emulsions was measured by using a Haake RV20. The measurements were performed by increasing the shear rate from 0 to 11.7 s^{-1} and from 0 to 117 s^{-1} respectively within two minutes. The viscosities were calculated from the flow curve at shear rate 10 s^{-1} for both the waterfree oils and the w/o-emulsions.

Oil weathering

The oils were artificially weathered in the laboratory before they were used in this study. The weathering processes taken into account are evaporation and w/o-emulsification.

The natural evaporation from an oil slick was simulated by a one stage distillation procedure, also called "topping" (modified ASTM DF86/82, Stiver and Mackay, 1984). The distillation removes the most volatile components from the oils and the degree of weathering is determined of the distillation temperature. The terminology "Oseberg 250°C+" indicates an Oseberg crude where the one stage distillation is continued until the vapor temperature has reached 250°C.

The w/o-emulsions were prepared by a modified rotating flask apparatus (Mackay and Zagorsky, 1982). The cylindrical separation funnels (0.5l) containing seawater and oil (volume ratio 1:1) were rotated (30 rpm) for a period of 24 hours (Daling et al., 1990). The weathering degrees of the oils used in this study are given in table 1.

Table 1: The oil types used in this study and the degrees of weathering for both waterfree and w/o-emulsions. The percentages are the water content in the w/o-emulsions.

	Oil viscosity		Emulsion viscosity	
		(cP*)		(cP*)
Oseberg crude	150°C+	100	150°C+/50%	500
Gullfaks crude	250°C+	810	250°C+/50%	4300
Veslefrikk crude	150°C+	90	150°C+/50%	1500
IF-30 Bunker fuel	150°C+	3200	150°C+/50%	10000

* measured at shear rate 10 s^{-1}

Oils types used in this study

Very limited data material exist concerning the chemical properties of the crudes from the arctic areas of Norway. The oils used in this "arctic study" have for this reason been selected among the crudes produced in the North Sea. The oils have been selected to give a large variation in their physico-chemical properties. A short description of the different oils used in this study is given below.

Oseberg blend crude is a medium heavy North Sea crude (0.853 kg/l) with a low wax and medium asphaltene content (0.7 and 1.4 wt.%). These values are for the fresh crude while the weathered oil used in this study (150°C+) has a pour point of 9°C.

Gullfaks crude is a medium heavy North Sea crude (0.882 kg/l) with a low wax and very low asphaltene content (1.6 and 0.07 wt.%). This is a naphthenhic crude where most of the n-alkanes are biodegraded by microorganisms in the reservoir. The pour point for the fresh crude is -30°C while the weathered oil used in this study (250°C+) has a pour point of 0°C.

Veslefrikk crude is a light paraffinic North Sea crude with a relatively high wax content (4.6 wt.%) and a low asphaltene content (0.1 wt.%). The fresh crude has a pourpoint of 6°C while the weathered oil used in this study (150°C+) has a pour point of 15°C.

Bunker fuel (Intermediate Fuel-30) is a refinery product which contains approximately 65% bunker-C (IF-340) and 35% gasoil which gives a density around 0.936 kg/l. Intermediate fuels are defined from their viscosities and IF-30 has a viscosity of 30 cP (50°C). IF-30 has a low wax and medium to high asphaltene content (2.5 and 4.1 wt.%). The oil used in this study (150°C+) has a pour point of 0°C.

Dispersants: The dispersants used in this study are listed in table 2.

Table 2: Dispersant used in this study

Dasic slickgone NS	IKU-9	Inipol IPC
Enersperse 700	Dasic slickgone LTS	Enersperse 1037
Dasic fresh water	Corexit 9527	Finasol OSR-52
Corexit 9550	Inipol IPF	Dispolene 388
Finasol OSR-5		

RESULTS AND DISCUSSIONS

Screening testing of dispersants

To test a broader selection of commercially available oilspill dispersants, 14 dispersants were tested in a screening stage of the study. These dispersants were tested with two North Sea crudes (Oseberg and Gullfaks), two salinities (3.3 and 0.5%) and at 0°C.

Figure 1 shows dispersant effectiveness with Oseberg 150°C w/o-emulsion containing 50% water with a viscosity of 500 cP. Figure 1 a-b illustrate that many dispersants which show a high effectiveness at 3.3% salinity have a rather poor effectiveness at 0.5% salinity. Only 3 dispersants of the 6 at "high" salinity in figure 1a have an effectiveness above

40% at "low" salinity in figure 1b. In addition to the 3 common dispersant in figure 1a-b which have an effectiveness above 40%, 2 products especially designed for fresh water use (Dasic fresh water and Inipol IPF) have an effectiveness above 40% in figure 1b. None of the tested dispersant showed an effectiveness above 60% at low salinity in figure 1b.

The most drastic drop in effectiveness was observed for Dasic NS and IKU-9 which both decreased their effectiveness from approx. 80% to below 15%. The fact that these products are especially optimized for North Sea conditions (3.3% salinity) may explain this drastic reduction in effectiveness.

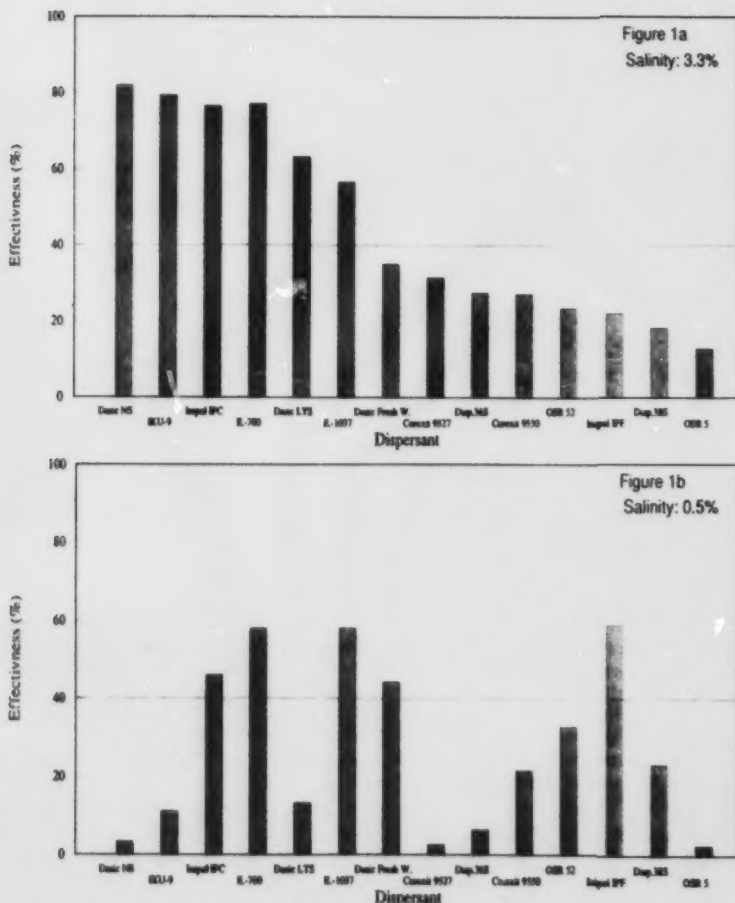


Figure 1: Effectiveness of the 14 dispersants measured with the IPF-test at 0°C and with an Oseberg w/o-emulsion (150°C+/50% water). Figure 1a is with 3.3% salinity and 1b is with 0.5% salinity.

An possible explanation for this significant decrease in effectiveness at low salinity may be that the surfactants behave differently when the salinity changes. This change in surfactant behavior may be caused by e.g. different protolysation which changes the Hydrophilic-Lipophilic-Ratio (HLB). Another possible reason for the decrease in effectiveness could be different tendencies for the surfactants to leak from the oil into the water phase when the salinity of the water changes (Mackay, 1985).

The w/o-emulsion with the weathered Gullfaks crude in figure 2 has a higher viscosity (4300 cP) than the Oseberg crude (500 cP) and is generally more difficult to disperse. However, the main trends in figure 1b and 2 are the same and the 5-6 most effective dispersant are the same.

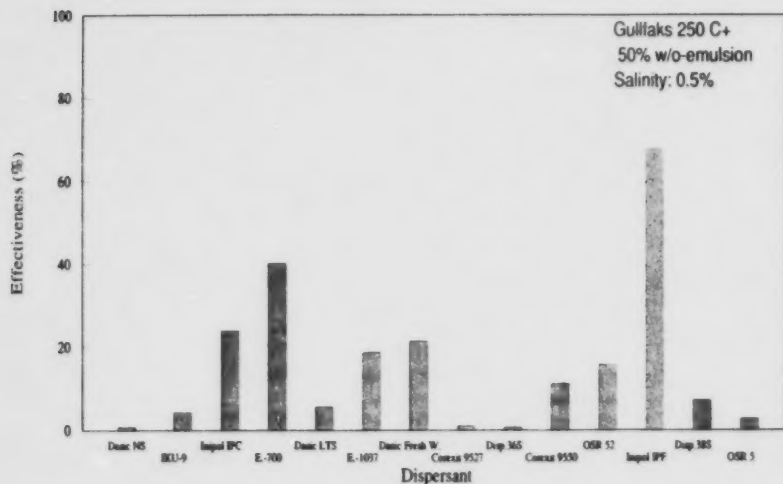


Figure 2: Effectiveness of the same 14 dispersants as in figure 1 at 0°C and 0.5% salinity, but with Gullfaks crude w/o-emulsion (250°C with 50% water).

From this screening test 5 products were selected for an extended study. These products were:

- * Inipol IPC
- * Enersperse 700
- * Finasol OSR-52
- * Dasic Fresh water
- * Inipol IPF

Extended dispersant testing

The five dispersants selected in the screening study were tested with four different oil types at two different salinities (3.3% and 0.5%). These four oil types were used at two different weathering degrees (waterfree and w/o-emulsion). The oil types and weathering degrees used in this study are given in table 1.

The effectiveness of the five dispersants on these oiltypes is given in figure 3 for the waterfree oils and in figure 4 for the w/o-emulsions.

Ranking of the dispersants: A mean value to be used for the ranking of the dispersant can be calculated as mean effectiveness for all oil types (both waterfree and w/o-emulsions). This ranking is given in table 3.

Table 3: Ranking of the tested dispersants both for 3.3% and 0.5% salinity. The effectiveness values are mean values for all four oil types for both waterfree and w/o-emulsions. Both mean effectiveness and ranking numbers (in brackets) are given.

	Dispersant ranking	
	0.5%	3.3%
Inipol IPF	65% (1)	25% (5)
Enersperse 700	43% (2)	67% (2)
Finasol OSR-52	33% (3)	38% (3-4)
Inipol IPC	32% (4)	69% (1)
Dasic Fresh-water	24% (5)	38% (3-4)

The most effective dispersant among these 5 products at 0.5% salinity is Inipol IPF, but the same dispersant has the lowest effectiveness at 3.3% salinity. These five dispersants were selected from an initial screening of a total of 14 dispersants and should be representative for the commercially available dispersants today. This large difference in effectiveness at 0.5% and 3.3% salinity for Inipol IPF indicates a lack of dispersants on the market with high effectiveness over a wide range of salinities. Enersperse 700 has the highest overall effectiveness with a medium to low (67-43%) effectiveness at both salinities. This ranking is based on mean values for all the four oil types (both waterfree and w/o-emulsified oils), but the relative ranking is surprisingly consistent for the different oil types (see figure 3 and 4).

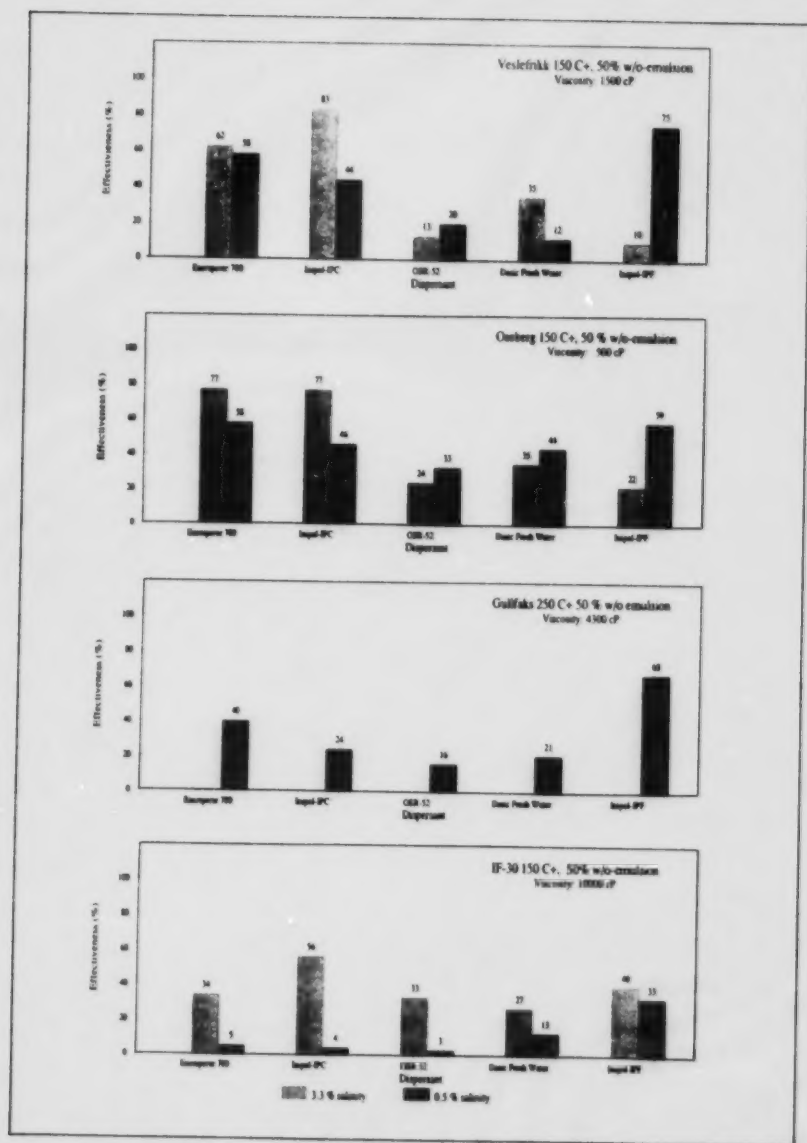


Figure 4: Effectiveness of five dispersants measured with the IFP-test on four different w/o-emulsions at 0°C. Tests were performed at salinities 3.3% and 0.5%.

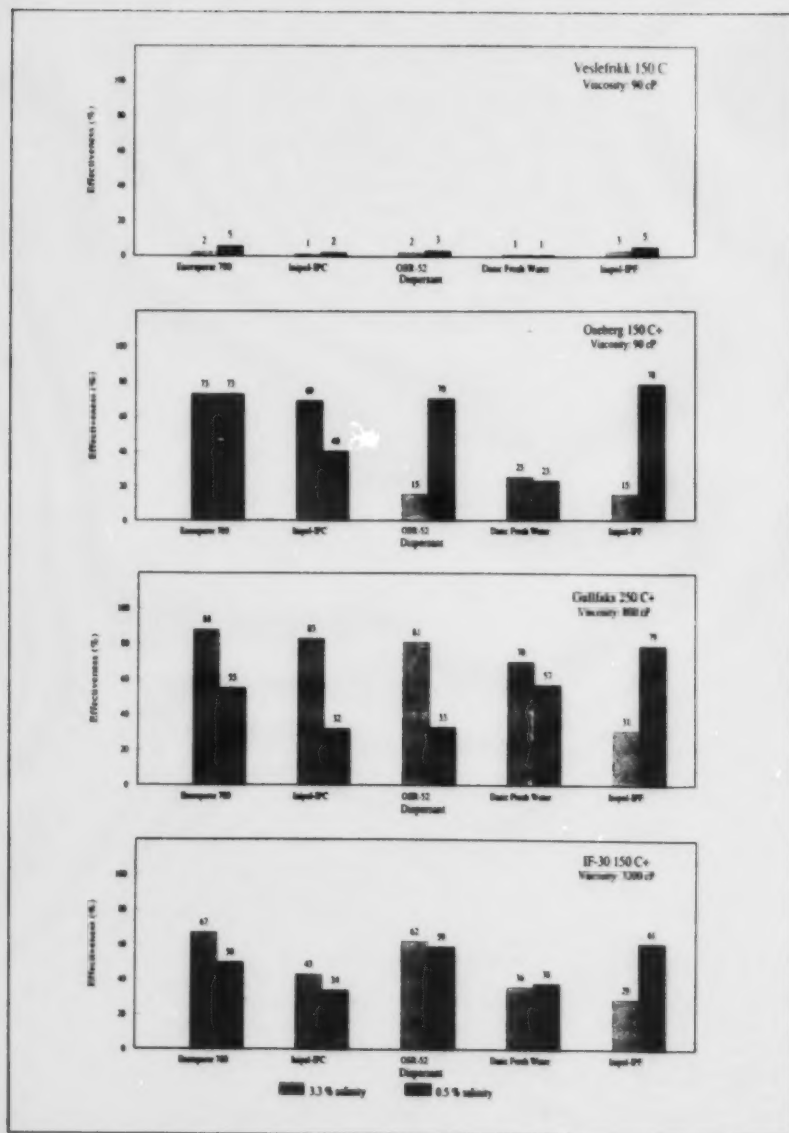


Figure 3: Effectiveness of five dispersants measured with the IFF-test on four different waterfree oils at 0°C. Tests were performed at salinities 3.3% and 0.5%.

Effectiveness with different oil types: For the waterfree oils of the paraffinic Veslefrikk crude the effectiveness of all dispersants was very low (<5%). This is due to a high pour point (15°C) compared to the test temperature (0°C) which often is the situation with wax-rich crudes at low temperatures (Brandvik et al. 1990). Surprisingly, this was not the case with the 50% w/o-emulsion with the same crude. This may be explained by the wax particles gathering at the water-oil interface to stabilize the water droplet in the w/o-emulsion. The tendency to form wax crystal structures in the oil may then be lowered since some of the wax particles are bound at the water-oil interface.

The effectivenesses of the five dispersants show some similar trends on both Oseberg and Gullfaks crudes in this study.

The w/o-emulsion made from the viscous IF-30 bunker fuel had the lowest dispersability of all the w/o-emulsions, especially for the w/o-emulsion made from the low salinity water. Only Inipol IPF of the tested dispersants was able to significantly break this high viscous w/o-emulsion and disperse the oil at low salinity.

Salinity effects: Of the 14 tested dispersants (both in the screening and in the extended study) only Inipol IPF was significantly more effective at low salinities. Finasol OSR-52 and Dasic fresh water showed in some cases a higher effectiveness at low salinity, but these observations do not represent significant trends. Some theories which may explain that the surfactants are acting differently at low salinities are proposed in the screening section earlier in this paper.

CONCLUSIONS

The results from this study show that many dispersant which previously have shown a high effectiveness at high salinity (3.3%), may give a very low effectiveness under low salinity conditions (0.5%). This is of significant operational importance in arctic oil spill combat operations since the salinity vary due to ice melting.

Recently developed products especially designed for low salinity use (e.g. Inipol IPF) are very effective at low salinities, but suffers from a rather poor effectiveness at higher salinities.

This study of dispersant effectiveness under arctic conditions shows the need for further development of dispersants with high effectiveness both at low temperature (0°C) and over a wider range of salinities (e.g. 3.3% to 0.5%).

It is also important to note that dispersants generally have different effectivenesses on different oil types (e.g. waxy or naphthenic crudes, asphaltene rich crudes and bunker fuels).

This effectiveness testing of commercial products is done only on a limited number of oil types and with one test method. Our conclusions may therefore not be valid e.g. for other oil types. The authors are not responsible for any use

of these results in the marketing of the named products in this study.

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PHYSICAL AND CHEMICAL STUDIES ON OIL SPILL DISPERSANTS: EFFECTIVENESS VARIATION WITH ENERGY

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SUMMARY

A study of the relationship between dispersant effectiveness and energy was performed in three different laboratory apparatus which use rotational motion to generate mixing energy. The stability of the resulting emulsions was gauged by measuring the amount of oil that remained in the water column over time.

The findings are that each oil/dispersant combination shows a unique threshold or onset to dispersion. The effectiveness goes up linearly with energy, expressed as flask rotational speed. Natural dispersion was also measured and shows similar behaviour to chemical dispersion except that the thresholds occur at a higher energy and effectiveness rises more slowly with increasing energy. Effectiveness (defined as the percentage of oil in the water column) rises rapidly to 100% with increasing energy for light oils treated with chemical dispersants. Heavier oils will disperse but to lesser effectiveness values.

Effectiveness varies significantly with quantity of dispersant amount. Stability of the resulting emulsion is affected by dispersant amount. Effectiveness can be viewed as a trade-off between energy, stability and dispersant quantity. As energy and dispersant quantity are increased, so is the effectiveness. Stability of the resulting emulsion is relatively independent of energy, but dependent on the amount of dispersant. High dispersion can be achieved using high energy and low dispersant amount, however, the resulting dispersion is less stable than one using more dispersant.

INTRODUCTION

Energy has been ascribed as the principle reason for the varying results of dispersant effectiveness results in the field and in the laboratory. Difficulties in varying or measuring this energy have left the variation of dispersion and energy largely unstudied. Energy is a complex topic.¹ Descriptions of what is meant by relevant energy to oil dispersion varies. One means to describe energy is by measuring the wavelength and amount of turbulence in the near surface.² Another definition is that of steepness of waves and their periods.³ Several discussions on the relationship between dispersion and energy have taken place, but little experimental work has been published.^{4,7} Fundamental literature on surfactants also does not propose energy relationships.^{5,9}

Many different types of dispersant test procedures and apparatus are described in the literature. One estimate places this at 50 different tests or procedures.¹⁰⁻¹⁵ Little work has been done on determining the reason for the poor correlation between test results. Most of the investigators cite energy as being the most significant factor. The general conclusion has been that the differences in energy levels and the way these have been applied to the oil/water mixture result in effectiveness values that are unique.

EXPERIMENTAL

Several rounds of experiments were conducted to determine the effect of varying energy. Several oils were used in these tests. Table 1 lists these oils and gives their basic physical properties. The dispersant used in this study is the Exxon product Corexit 9527 (abbreviated C9527 in some tables in this paper). All runs where dispersant was used, were performed with dispersant already mixed in the oil at a ratio of 1 to 25 by volume. This practice was adopted to achieve more repeatable results as determined in earlier experiments where both premixed and drop-wise addition were used.¹³ Saltwater was prepared with sodium chloride to 33 oo/o or degrees salinity. All tests were done at a temperature of 20 °C. Apparatus, oil and water were left at these temperatures for at least 20 minutes before the beginning of each test to ensure thermal equilibrium. All tests were done in thermally-controlled chambers.

TABLE 1		TEST OIL PROPERTIES	
OIL	DESCRIPTION	KINEMATIC VISCOSITY	DENSITY
		(mm ² /s at 5 °C)	(g/mL at 15 °C)
ASMB	ALBERTA SWEET MIXED BLEND	8	0.84
ARABIAN LIGHT	ARAB BLEND	40	0.87
BUNKER C LIGHT	LESS-VISCOUS BUNKER C	200	0.93
NORMAN WELLS	NORTHERN CANADIAN CRUDE	7	0.83
NORTH SLOPE	PRUDHOE BAY CRUDE	55	0.88

An apparatus, called simply "the high energy test" in our laboratories, was developed to measure dispersion at very high energy levels. This vessel is square and of dimensions 30 cm. on all sides. The effect of the corners is to create high levels of turbulence. The volume of oil and water were 5 L and 0.25 mL to yield an oil-to-water ratio of 1:20,000. This ratio was shown in a previous paper to yield optimal results. The mixing time is 20 minutes and the settling time is 10 minutes before samples are taken. The mixing energy is supplied by a Brunswick

shaker consisting of a moving table. This shaker is capable of rotational speed variations from 50 to 450 with relatively good repeatability. The revolutions meter on the shaker is calibrated periodically with a tachometer to ensure accuracy. A pipette is used to remove a 30 mL sample from the apparatus after the settling time.

Analysis for all four apparatus is performed by taking a sample of water from the test vessel after the run is complete, extracting the water with a solvent and measuring the absorbance at three visible wavelengths (370, 340, and 400), and then assigning effectiveness on the basis of a calibration curve. Calibration curves are prepared in a manner similar to the actual runs. Water is used in these calibration runs to ensure that extraction efficiency is compensated for and to compensate for the coloration addition of small water droplets.

EXPERIMENTAL RESULTS

Results of tests are shown in Table 2 and Figure 1. This figure illustrates the results of dozens of experiments. The findings are as follows: that dispersion increases very rapidly from a low value to nearly 80 to 100% and that natural dispersion onset occurs at an energy level higher than that for chemical dispersion, and finally that the natural dispersion curve has a lesser slope than that for chemical dispersion.

The energy is sufficient in the high energy apparatus to disperse Bunker C light. Tests on regular Bunker C did not yield dispersion chemically or naturally. During the natural dispersion runs and partially during the chemical runs, the Bunker C grouped into large droplets on the surface. This is indicative that the energy in the apparatus is insufficient to disperse this oil or that this oil is indispersable under normal conditions. Onsets of natural dispersion lag the chemical dispersion and the curves of natural dispersion have a lesser slope than those for chemical dispersion. In addition, the heavier oils tested do not go to as high a dispersion level as other oils. This is indicative that they are not as readily dispersable as the ASMB. Another trend observed is that the order of chemical and natural dispersion onsets for the oils tested, are the same and are similarly spaced with respect to energy. The effect of chemical dispersant is to decrease the onset of dispersion and increase the amount by a large factor.

Some preliminary work has been done on assessing the difference in dispersion at high and low energies. This work indicates that dispersions formed at lower energies are more stable. Experiments on the amount of oil that remains dispersed in the water column after 24 hours is about 60% for the high energy dispersion and 80% for the low energy dispersion. The difference may well be the amount of dispersant in the droplets. The preliminary results of these tests are illustrated in Figure 2. This figure shows only results from tests conducted using the dispersant Corexit 9527. Work on stability of the resulting emulsions continues.

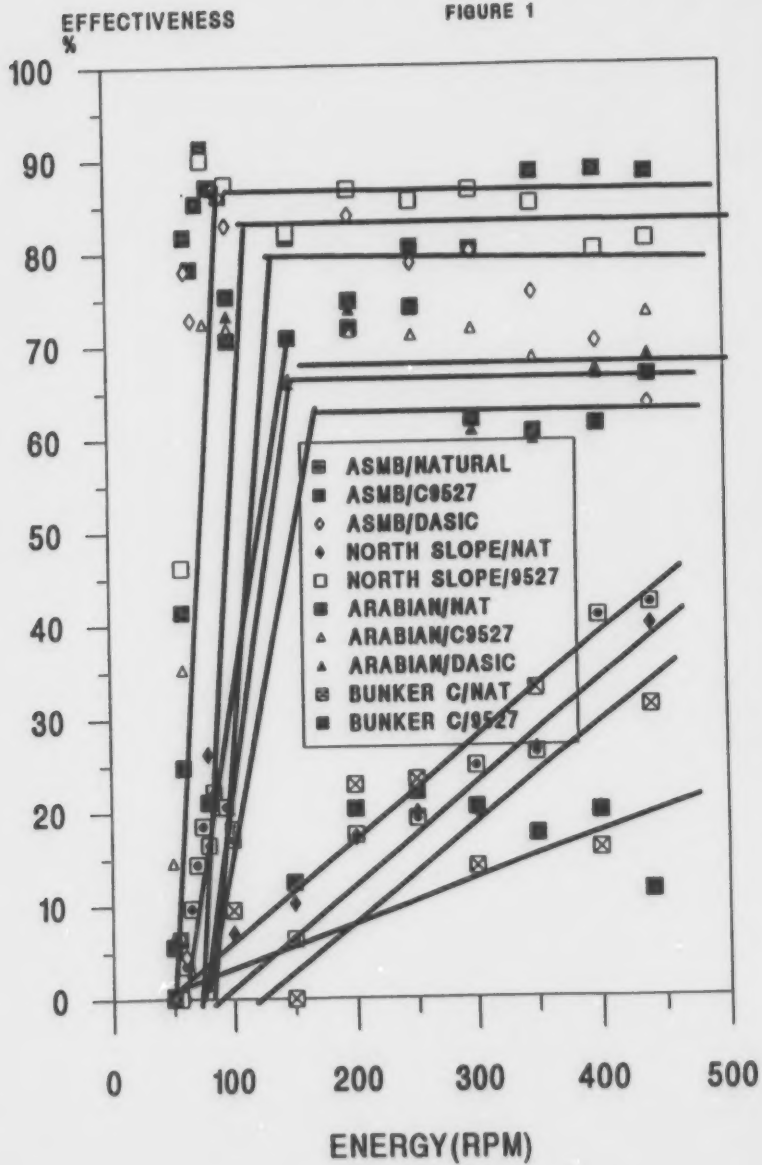
TABLE 2 EFFECTIVENESS VALUES FOR FOUR OILS

ENERGY (RPM)	ALBERTA SWEET BLEND			NORTH SLOPE		ARABIAN LIGHT			BUNKER C LIGHT	
	NATURAL	W/C9527	DASIC	NATURAL	W/C9527	NATURAL	W/C9527	DASIC	NATURAL	W/C9527
440	42.0	88.2	63.4	39.7	81.0	11.4	73.2	68.7	31.1	66.5
400	40.7	88.6	70.1	20.0	80.0	19.9	67.2	66.6	15.9	61.3
350	26.2	88.4	75.4	26.5	85.0	17.5	68.5	59.7	33.0	60.5
300	24.8	80.1	79.9	20.0	86.5	20.4	71.6	60.7	14.0	61.9
250	19.2	80.4	78.7	19.8	86.4	22.1	71.0	73.7	23.4	74.0
200	17.5	71.8	83.9	17.2	86.7	20.3	71.4	73.8	22.9	74.7
150	6.4	81.6	70.5	10.2	82.1	12.4	66.4	65.9	0.0	70.8
100	17.1	75.3	82.9	7.0	87.3	18.2	71.9	73.2	9.5	70.6
95	20.6	86.1	86.0							
90	20.6	87.0								
85	22.2	87.1								
80	16.5	91.3		26.2	90.0	21.1	72.4			
75	18.5	85.3								
70	14.4	78.3	72.8							
65	9.7	81.7	78.0							
60	3.5	41.4	4.5	0.0	46.2	24.8	35.3			
55	0.3	6.4	6.6	0.0	0.0					
50	0.0	0.3	0.0	0.0	0.0	5.6	14.6	6.6	0.0	0.0

LEGEND W/C9527 = WITH DISPERSANT COREXIT 9627

COMPOSITE DATA

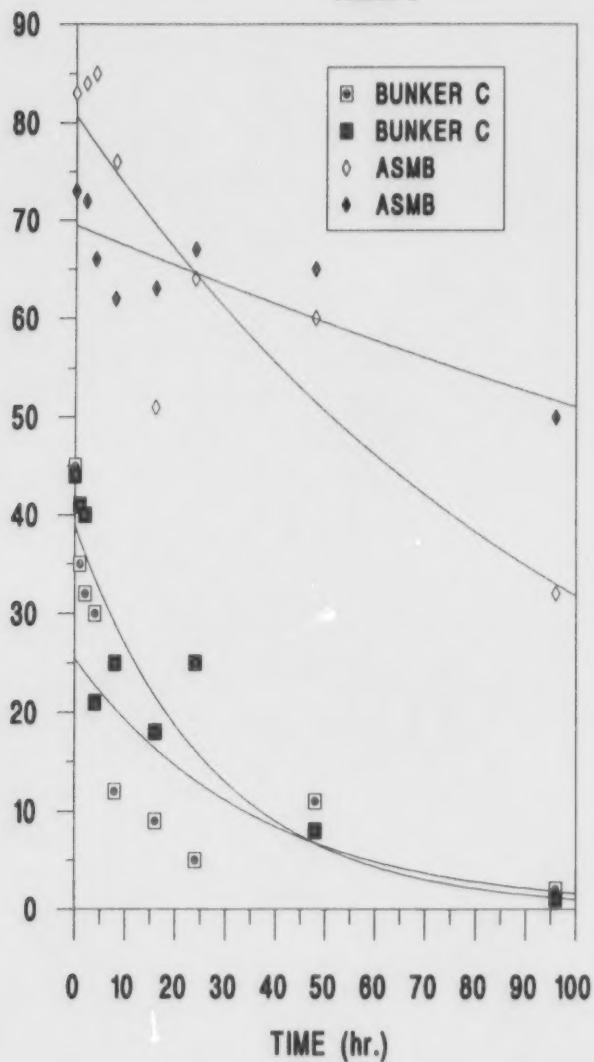
FIGURE 1



STABILITY MEASUREMENTS ON TWO OILS WITH COREXIT 9527

OIL REMAINING IN
THE WATER %

FIGURE 2



SUMMARY AND CONCLUSIONS

Chemical dispersion increases with energy in a linear fashion until a maximum is reached. For light oils this maximum is about 85%. For heavier oils this is about 65%. The dispersion curve is very steep, that is only a small amount of energy causes a large amount of change in dispersion. There exists an energy threshold below which little dispersion occurs. Chemical dispersion curves for different oils appear to be parallel. This may be indicative that the mechanism is fixed and only the threshold varies.

Natural dispersion is analogous to chemical dispersion except that the onset occurs at a higher energy and the increase with energy is much less.

Initial work has also been conducted on particle stability. This shows that there may be differences in the stability of dispersions at low and high energies. The difference does not appear in droplet size, but is probably due to the lesser amount of dispersant in those droplets formed at high energy. This lesser dispersant amount is simply a result of forming many more droplets at high energy with the same amount of dispersant.

The major question these experiments raise is how the energy in these tests relates to that at sea. There are a few observations which indicate that most typical sea energies actually occur at the low end of the energy spectrum shown in the test data presented here. In one test at sea, ASMB and Bunker C light were observed to start dispersing naturally around Beaufort 6.²⁰ The EKOFISK BRAVO oil was observed to disperse naturally at sea states around Beaufort 5 or 6.²¹ It is recognized that turbulent energy is the important factor for dispersion. Technology does not exist at this time to measure this type of energy at sea and in the laboratory. There may be potential for this in the future with laser doppler or hot wire instruments.

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ASAP: A State of the Art Oil Spill Model for Worldwide Application

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Applied Science Associates, Inc. (ASA) has formed a consortium with several major oil companies and two government agencies (U.S. and Canada) to develop a state-of-the-art oil spill model system for application to oil spill response and contingency planning. Members include the Canadian Petroleum Association, Chevron, the U.S. Army Corps of Engineers, Environment Canada, Exxon, Mobil and ASA. The system, ASAP, enables the user to predict the trajectory of an oil spill in the water anywhere in the world. Within half an hour of notification of a spill, the user is able to evaluate a variety of oil spill response scenarios. The model also has the capability to be updated based on observations of the oil distribution and composition.

The model is being developed for operation on personal and lap-top computers and will provide deterministic and stochastic spill forecast simulations. Embedded within the system are low resolution data for coastlines, bathymetry, currents and statistical winds. These data allow the model to be rapidly applied to any area in the world. The system will also accommodate high resolution data for areas of specific interest.

The model system relies on an easy-to-use graphical interface to make the many complex components of the system accessible. Environmental data is user-selectable and includes the ability to use constant, time series, spatially varying time series or statistically generated time series data.

ASA has developed a graphical interface in which the mouse is used to "paint" a few current vectors in the area of interest. The interface then fills in a current field which can be used by the oil spill model. Other innovative graphical interfaces include a gridding routine for creating new locations and a methodology for producing time and space varying winds.

The oil spill fates model allows the user to select which algorithms are to be used to predict the oil's drift, spread, evaporation, emulsification, shoreline interactions, dissolution, dispersion and ice-oil interactions. The model predicts the oil distribution (trajectories) and fate (mass balance) as a function of time for instantaneous or continuous spills from single or multiple, surface or subsurface sources. A library of oil types which can be easily augmented is included with the model.

Four classes of spill simulation can be performed within this system:

- 1) rapid trajectory forecasts, with limited mass balance computations;
- 2) full strategic forecasts: complete mass balance and cleanup computations, with some of all transformation processes engaged;
- 3) stochastic simulations, with limited mass balance;
- 4) receptor mode calculations.

Rapid trajectory forecasting, with updating capabilities, is viewed as the front-line mode for spill response. Complete mass balance trajectory computations using the full strategic model are useful in subsequent development of response strategies, comparison of alternatives, control and management of spill drills, and in a variety of hindcast situations. Stochastic simulations are used primarily for contingency planning and risk analysis, to determine most probable trajectory envelopes, and coastal or other areas at risk in the event of a spill. Receptor mode calculations are used to determine the most probable source of a past release of oil, given its present observed position.

The overall system supporting these modeling capabilities is shown schematically in Figure 1. The first screen which appears when the system is invoked displays this main menu and a map of the last location for which the system was used. Within a given location, a user may have more than one application, perhaps at different resolution levels.

A hypothetical session to set up a new area proceeds as follows. The user sits down at the PC, and invokes the system by entering its acronym, ASAP. A world map appears on the screen, with the main menu across the top. The user pulls down the "Location" items, then the "Create" sub-item (Figure 1.E). The system asks the user to specify the study area, either by typing in latitude/longitude coordinates, or using the system's zoom and windowing facilities. The system then extracts from the worldwide data base all geographical data pertaining to the specified area, and produces a grid system, which the user can then modify, if desired. When a satisfactory representation of the study area has been obtained, the user moves into the "Environmental" branch under "Data/Setup". Here the user can choose among a variety of options for selecting or creating winds, currents, ice cover, and water and air temperatures. Having created the needed environmental products, the user can now proceed to the "Model Run" branch, and carry out simulations.

The "Data" branch of the menu tree allows the user to access and augment the data sets underlying model simulations. "Geographical" data includes coastline, shoreline types, bathymetry and perhaps some cartographic overlays supplied by the user, such as roads, airports, ports, and towns. The "Edit/Setup" option allows the user to establish a new application area, or to make alterations to one already established. The "Add" option will lead the user through the procedures for creating and importing new data sets at higher resolution than those supplied with the system. The "Environmental" data branch gives the user access to stored, pre-processed environmental data and data products (e.g., Markov matrices, historical wind time series, mean seasonal currents), and to sets of tools for altering, importing, computing,

and constructing environmental data products to drive the model. The "**Petroleum**" data branch allows the user to review or add to the library of crude oils and petroleum products in the system.

The "**Model Run**" branch of the menu allows the user to select among the different models available within the system, and specify and run various spill scenarios with them. It appears probable that we will be able to display model results in real time on the screen as the results are computed, at least for the fast trajectory model. In addition, results will also be stored in files keyed to the scenario name, and will be available for viewing, printing, and plotting under the "**Model Output**" branch.

Under the "**System**" branch will be available a variety of system management and communication tools. These will be designed to help manage space on the hard disk, as well as to facilitate import/export operations, and communication between/among users, in both real and spill drill situations.

ASAP is scheduled for completion in 1993. Even at its present stage of completion (approximately 60%), ASAP allows unparalleled response for arbitrary locations worldwide. A demonstration of the system will be presented at AMOP.

ASAP: WORLDWIDE OIL SPILL MODEL VERSION 0.6

WOSM	LOCATION	DATA	MODEL RUN	MODEL OUTPUT	SYSTEM	HELP	QUIT
ABOUT	SELECT CREATE DELETE SUMMARY	GRIDS WINDS (A) CURRENTS (B) BATHYMETRY (C) ICE (D) PETROLEUM GIS NOTEBOOK	TRAJECTORY TRAJECTORY & FATES RECEPTOR MODE STOCHASTIC MODE	TRAJECTORIES OIL DISTRIBUTIONS TABLES & SUMMARIES	SYSTEM PARAMETERS EXPORT/IMPORT DELETE FILES COMPRESS FILES BACKUP FILES	SYSTEM HELP	EXIT TO DOS

- (A) — GENERATE POINT SOURCE TIME SERIES
 — GENERATE SPATIAL WIND FIELD
 — HISTORICAL/CLIMATOLOGICAL (500 STATIONS AVAILABLE WORLDWIDE)
 — IMPORT MET MODEL DATA
- (B) — GENERATE CURRENT FIELD
 — GENERATE TIDAL DATA
 — CLIMATOLOGICAL WORLDWIDE DATA
 — IMPORT HYDRODYNAMIC DATA
- (C) — VIEW WORLDWIDE BATHYMETRY
 — IMPORT LOCAL BATHYMETRY
- (D) — GENERATE ICE FIELD

Figure 1. Schematic structure of ASAP model system

RESEARCH INTO 90 OCTANES GASOLINE (NORMAL) EVAPORATION IN ITS NATURAL ENVIRONMENT.

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1.- Introduction.

A crude-oil or its derive by-producto such as gasoline can reach a sea or a beach and pollute ir in many different ways: e.g. loading and unloading of oil-tankers, its ballasting of through shipping accidents, etc. Te evaporation process is considered one of the must important of all those phenomena affecting spilled hydro-carbon mixtures because of its high volatility capacity. In this way large quantities of hydro-carbons are released into the atmosphere within a short period of time and may cause breathing difficulties and situations with high risks of fire.

Research into multi-component mixtures are usually carried out in laboratory condicions whereby the different parametres affecting the evaporation process can be regulated. The obtained findings will differ from those evaporation processes carried out under varying climatic condicion and in general are difficult to be controlled in a natual environment. Besides the characteristics of the components of a spilled hydro-carbon mixtures other factors influencing the evaporation ares the following: temperature, air velocity, solar radiation as well as the specific condicions set by the environment such as its sea-surface and bech sand with its corresponding texture, etc.

The overall objective of this research paper is to study the 90 octanes (normal) gasoline evaporation simulating its spillage on a sea surface or on beach sand with different texture, whereby the effects of solar radiation, temperatures, air velocity, diferente sand textures of the spilled beach surface are being measured and the variation in evaporated fraction in function of time, its diffusivity, its density in discharge are being determined.

In any real crude-oil spill on water or on land, the information on the type of spilled product (whose physical and chemical characteristics can be found in the bibliography), the length of time needed for the evaporation process, the geographical features of the area, and climatic parametres are difficult to be obtained. In any research on multi-component hydro-carbons or gasoline mixtures the normal applied equations

aren't of much use because the parametres influencing this evaporation process are difficult to determine and will also change in time.

To correlate the evaporated fraction in function of time, the equation suggested by Bergueiro & Domínguez (1), which has already led to excellent results in hydro-carbon experiments under laboratory conditions, will be used in the research carried out in the laboratory (Marti, (2)), whereby F_m is the fraction of evaporated mass expressed in percentages of the evaporation with regards the initial spilled quantity

$$F_m = a \cdot \ln(1 + b \cdot t) \quad [1]$$

The before mentioned equation allows to determine the evaporated fraction for distinct time intervals. The parametres a and b are determined for the mathematical fitting through the Marquardt method.

2.- Determination of the diffusion of volatile components.

The diffusion process describes the movement of a substance A through other substances due to its concentration-gradient. The estimation of its diffusivity for multi-component mixtures is extremely difficult. Although there are different ways to determine it, they are very often applied to mixtures with fewer components but with their composition is known beforehand. Its application to multi-component mixtures such as a crude-oil or its derived by-products is very limited as its determination is a long and difficult process. Therefore, the determination of the diffusivity using existing methods is very difficult and highly complicated.

In this research paper the diffusion of volatile components in the remaining mixture in function of consumed time during the evaporation process has been determined through the equation of unsteady-state molecular transport. The outcomes of these equations vary according to the applied geometrical shape. The most similar geometric shape with known outcomes for a film spread out on a sea surface is a thin sheet with infinite length and width but with semi-infinite thickness and permitting a transfer of substances through one of its sides. Since one side is in contact with the sea water surface, the evaporation, diffusion, dissolution of its components is rather inferior compared to the quantity which is being exchanged through evaporation on the opposite side. The equation of unsteady-state molecular transport for this geometric shape is (4):

$$\begin{aligned}
 Y &= 2 \sum_{v=0}^{\infty} \frac{(-1)^v}{\left(n + \frac{1}{2}\right)\pi} \exp \left[\left(\left(v + \frac{1}{2} \right) \pi \right)^2 \cdot \cos \left(v + \frac{1}{2} \right) \pi n \right] = \\
 &= \frac{4}{\pi} \exp \left[-\frac{\pi^2 x}{4} \right] \cos \left(\frac{\pi}{2} \right) - \frac{1}{3} \exp \left[-\frac{9\pi^2 x}{4} \right] \cos \left(\frac{3n\pi}{2} \right) + \\
 &+ \frac{1}{5} \exp \left[-\frac{25\pi^2 x}{4} \right] \cos \left(\frac{5n\pi}{2} \right) + \dots
 \end{aligned}$$

whereby:

$Y = (C_e - C_a)/(C_e - C_{a0})$: Concentration of adimensional propriety.

C_e = Concentration of the volatile components in the surrounding atmosphere.

C_a = Concentration of the volatile components in the gasoline taken at any time.

C_{a0} = Concentration of the volatile components in the gasoline at initial stage.

$X = D_{AB} \cdot t / (r_m)^2$: Adimensional time.

D_{AB} = The diffusivity.

t = Time (s).

r_m = Thickness of the crude-oil film.

The before-mentioned equation was obtained under the following assumptions:

- At the beginnig, the concentration of volatile components is released in the overal system in a uniform way. The same happens during the evaporation process as a very thin film is used (in terms of milimetres).
- The concentration of volatile components in the atmosphere is rather inferior to the quantity present in the film. This is because of the air movements which transport the hydro-carbons away from the spillage zone.
- The resistance to the substance transference from the upperside of the film into the surrounding environment can be considered as minimun. Any mayor resistance is due to the diffusion of volatile through non-volatile components.

The before-mentioned equation is an infinite series and gives a good illustration of the problems you may be faced with when working with changing conditions. For high values of the adimensional time the series converges very quickly, whereby only the first obtained outcomes are of importance. When sort length of time are involved, the process of convergence is much slower.

There are grafics outcomes for the before-mentioned equation in terms of its adimensional parameters Y , X , $m=K_c \cdot r_m$ y $n=r/r_m$. The way of estimating their diffusivity is the following:

First, "Y" should be determined and is considered as the quotient of the concentration of evaporated volatile components at any time interval (C_a) and the initial number of volatile components (C_{a0}). Both are expressed in terms of total mass inerts. The concentration of volatiles at C_{ae} is considered as the zero point. Therefore $Y=C_a/C_{a0}$. The concentration of the initial quantity of volatiles can be determined by leaving a known mixture to evaporate during a period of time until there is practically no variation in mass. The difference in initial mass and final mass will give the mass of volatile components at the initial stage of the evaporation process. When the evaporated mass at each interval is determined, its corresponding estimation should be carried out.

At the initial stage the needed time interval to evaporate a gram of gasoline is relatively short. However it increases the longer the evaporation process lasts. Then the fraction of total evaporated mass should be determined. This value for F_m and for a and b are substituted in the equation [1] and so permits you to know the evaporation interval. In a similar way with known values for F_m the density of the remaining mixture through the suggested equations in enclosure I can be then determined.

The values obtained for the density of the mixture are needed for determining the thickness of the gasoline film. In the experiments without sand its thickness is the quotient of the remaining gasoline and the size of the board. For boards with sand its thickness is calculated by using an experimental correlation between its volume and thickness. In both cases the value for r_m is considered half the average thickness between two time intervals with the centre of the board as reference point.

Then, when this values for r_m , X and t are known, the value for the diffusion D_{AB} at a certain time interval can be found.

The other parametre which is determine in this research paper is the variation in mass flow densitics N_j , and is expressed in $\text{kg/m}^2\text{s}$. This parameter gives you information on the evaporation process and under known time intervals is the quotient of the evaporated mass at these time intervals divided by the multiplication of the mass transference surface and the length of the evaporation process. The mass transference surface on boards without sand is much more higher than boards with sand, even when the latter gas the same transference surface and without taking into account the size of the sand particle.

3.- The experiment stage.

The volatile percentage for gasoline was 99.9 %. With regard to the evaporated volatiles a constant evaporated mass of 0.5 g/interval was used through out the experiment. Therefore, a constant value for Y ($Y=0.016$) throughout the process was obtained. Using the obtained value for Y, X was determined through the equation [2] and so was calculated the value for $X=1.630$

$$X = 0.01135 - 0.90123 \cdot \text{Lg}(Y) \quad \text{Eq. (2)}$$

In all the experiments 30 g of the gasoline, whose characteristics are shown is in enclosure I, was spilled on 73.44 cm^2 sized boards. The samples were weighed at fixed intervals and through, the difference in weight, the evaporated fraction at the fixed interval ($\%F_m$) could be determined.

The boards were installed on frame-works in the outside and exposed to the air. At any time the air velocity was measured by using a SEAK-AM7, with a desviation of $\pm 0.1 \text{ m/s}$. These assumptions have been named environmental conditions or "c.a".

Information cn solar radiation was obtained through the weather station of Palma de Mallorca. In table I the dominating climatic parametres during the experiments are described.

To study the effects of sand on the evaporation process, 140 g of lime-stone sand taken from the El Arenal beach (Palma bay, Spain) was placed and spilled on 30 g of gasoline. Three types of sand with different texture were used in the experiments: i.e. normal sand (unsieved sand whithout stones and shells; medium sand (with texture diametre ranging from 0.25 to 0.5 mm and coarse sand (with texture diamete ranging from 0.5

to 1 mm). On the sand boards the transference surface reduced to 30.067 cm².

Evaporated time (min)	temperature (°C)	Average air velocity (m/s)	Direct radiation (J)
5	20.4	0.91	57.9876
10	20.7	1.29	53.2451
15	21.0	0.64	64.5101
20	21.4	0.67	68.8230
25	21.6	0.62	79.4575
30	21.9	1.08	61.6757
35	22.2	0.66	68.3211
40	22.5	0.65	70.2281
45	22.8	0.81	75.7238
50	23.1	1.06	79.7330
55	23.5	1.11	76.9901
60	23.9	1.02	70.7136
65	24.2	1.03	74.5330
70	24.5	0.47	78.1564
75	24.7	0.90	84.5330
80	24.9	0.97	78.8921
85	25.1	1.10	81.3647
90	25.4	0.69	78.4917
95	25.7	1.25	87.0136
100	25.9	1.01	89.7195
110	26.3	0.95	91.0184
120	26.7	0.53	102.6776
130	26.9	0.99	95.6441
140	27.0	0.55	87.3169
150	27.0	0.57	91.7896
160	27.1	1.19	102.6507
170	27.2	1.00	101.3929
180	27.2	0.49	16.3725
190	27.0	1.21	94.4563
200	26.9	0.95	95.0771

Tabla I.- Dominating climatic parametres during the evaporation experiments of 90 octanes gasoline.

Table II a V shows the variation of evaporated fraction in function of time as well as the mass flow density. The variation in air velocity at this same interval and the quotient of the

gasoline temperature and air are also described. The values for a and b are obtained through the Marquard fitting method.

Time (min)	Air Velocity (m/s)	T _a plate/ T _a air.	F _m (%)
5	0.91	0.63	26.70
10	1.29	0.58	38.98
15	0.64	0.54	49.45
20	0.67	0.52	57.06
25	0.62	0.49	62.03
30	1.08	0.49	66.67
35	0.66	0.51	70.07
40	0.65	0.56	73.21
45	0.81	0.60	75.81
50	1.06	0.65	78.16
55	1.11	0.67	80.19
60	1.02	0.68	82.34
65	1.03	0.70	83.96
70	0.47	0.71	85.25

Table II. Evaporation conditions: Direct Radiation. Air Velocity: Environmental conditions.

Fitting data:

$$a = 23.9012$$

$$b = 0.4762$$

Time (min)	Air Velocity (m/s)	T _a plate/ T _a air.	F _m (%)
5	0.91	0.82	7.56
10	1.29	0.80	16.47
15	0.64	0.77	25.03
20	0.67	0.74	30.97
25	0.62	0.71	38.51
30	1.08	0.71	44.02
35	0.66	0.72	48.75
40	0.65	0.75	52.09
45	0.81	0.75	55.63
50	1.06	0.77	58.73
55	1.11	0.77	61.63
60	1.02	0.77	64.23
65	1.03	0.78	66.24
70	0.47	0.78	68.18
75	0.90	0.80	69.92
80	0.97	0.82	71.19
85	1.10	0.83	72.51
90	0.69	0.84	73.72
95	1.25	0.85	74.49
100	1.01	0.87	75.32
110	0.95	0.87	77.03
120	0.53	0.87	78.46
130	0.99	0.88	79.69
140	0.55	0.90	80.62
150	0.57	0.91	81.75
160	1.19	0.92	82.54
170	1.00	0.93	83.19
180	0.49	0.94	83.76
190	1.21	0.95	84.31
200	0.95	0.95	84.82

Fitting data:

$$a = 26.8233$$

$$b = 0.1421$$

Table III. Evaporation conditions: Spilled on medium sand. Air Velocity: Environmental conditions.

Time (min)	Air Velocity (m/s)	T _a plate/ T _a air	F _m (%)
5	0.91	0.81	12.21
10	1.29	0.79	20.02
15	0.64	0.76	27.72
20	0.67	0.72	35.66
25	0.62	0.69	42.13
30	1.08	0.70	47.23
35	0.66	0.71	51.63
40	0.65	0.73	55.21
45	0.81	0.74	59.71
50	1.06	0.77	61.32
55	1.11	0.77	63.72
60	1.02	0.77	65.79
65	1.03	0.78	67.53
70	0.47	0.78	69.24
75	0.90	0.80	70.69
80	0.97	0.82	72.11
85	1.10	0.83	73.52
90	0.69	0.84	74.49
95	1.25	0.85	75.51
100	1.01	0.86	76.48
110	0.95	0.87	78.04
120	0.53	0.87	79.38
130	0.99	0.88	80.68
140	0.55	0.90	81.74
150	0.57	0.91	83.62
160	1.19	0.92	83.90
170	1.00	0.93	84.72
180	0.49	0.94	85.04
190	1.21	0.95	85.58
200	0.95	0.95	86.06

Fitting data:

$$a = 24.8796$$

$$b = 0.1906$$

Table IV. Evaporation conditions: Spilled on normal sand. Air Velocity: Environmental conditions.

Time (min)	Air Velocity (m/s)	T _a plate/ T _a air,	F _m (%)
5	0.91	0.80	15.07
10	1.29	0.77	24.23
15	0.64	0.75	33.01
20	0.67	0.71	41.16
25	0.62	0.68	47.51
30	1.08	0.69	52.47
35	0.66	0.70	56.61
40	0.65	0.72	59.51
45	0.81	0.74	62.02
50	1.06	0.76	64.53
55	1.11	0.77	66.61
60	1.02	0.77	68.52
65	1.03	0.78	70.49
70	0.47	0.78	71.96
75	0.90	0.80	73.26
80	0.97	0.82	75.20
85	1.10	0.83	76.21
90	0.69	0.84	77.43
95	1.25	0.85	78.20
100	1.01	0.87	79.41
110	0.95	0.87	80.52
120	0.53	0.87	81.68
130	0.99	0.88	83.22
140	0.55	0.90	83.98
150	0.57	0.91	85.04
160	1.19	0.92	86.03
170	1.00	0.93	86.88
180	0.49	0.94	87.52
190	1.21	0.95	88.07
200	0.95	0.95	88.56

Fitting data:

a= 23.1542

b= 0.2738

Table V. Evaporation conditions: Spilled on coarse sand. Air Velocity: Environmental conditions.

2.2.-The effects of the transference surface on the evaporation rate of the gasoline.

The values for a and b for de different mass transference surfaces were determined. These effects are showun in table VI.

Smoll Board	Medium board	Large board
Area=73,44 cm ²	Area= 91,61 cm ²	Area= 165,13 cm ²
a= 23.9012	a= 24.6035	a= 23.9334
b= 0.4762	b= 0.53556	b= 0.6443

Table VI.- Effects of the transference surface of the substance on the parametres a and b .

In the diagram I the percentage of evaporated mass (% Fm) against the factor time for the evaporation experiments of only spilled gasoline or spilled on sand are shows. The presence of sand slowed down the evaporation process with 130 minutes with obtaining the same final values.

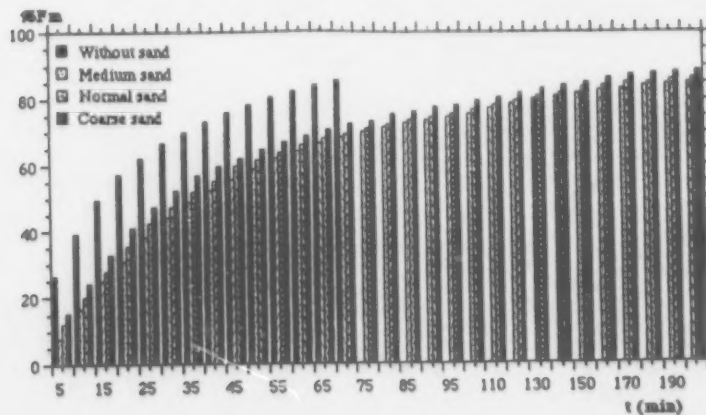


Diagram I.- Percentage of evaporated mass (% Fm) against time for gasoline evaporation experiments without sand of spilled on sand of different texture (medium, normal, coarse).

Diagrams II to V show the diffusivity against time for evaporated fractions of 0.5 g.

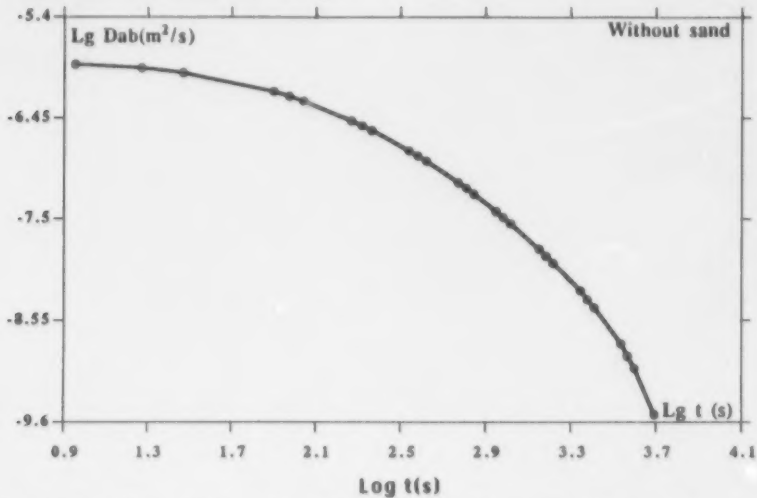


Diagram II.- Plot of diffusivity values against time for evaporated fractions of 0.5 g for gasoline evaporation experiments without sand

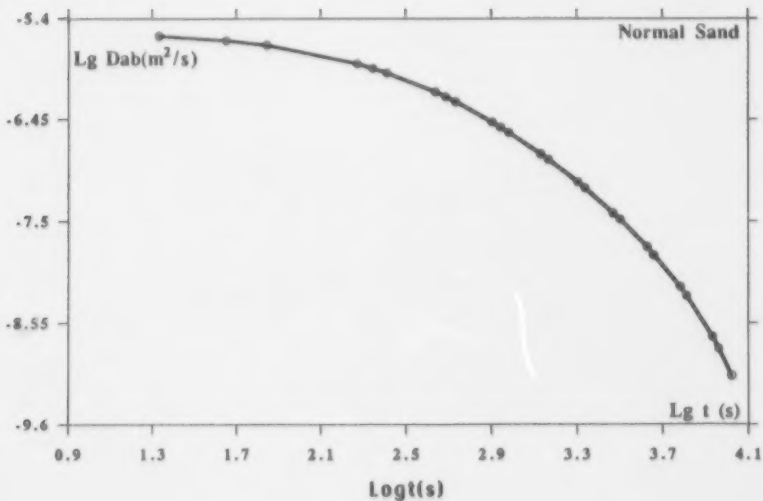


Diagram III.- Plot of diffusivity values against time for evaporated fractions of 0.5 g for gasoline evaporation experiments with normal sand.

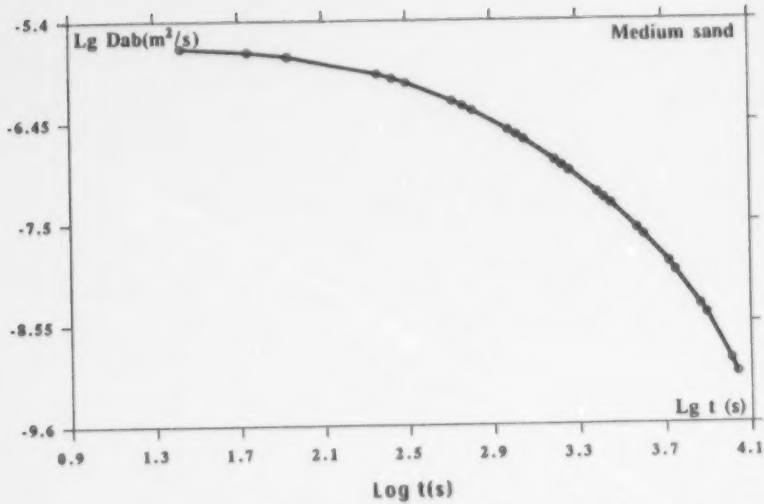


Diagram IV.- Plot of diffusivity values against time for evaporated fractions of 0.5 g for gasoline evaporation experiments with medium sand

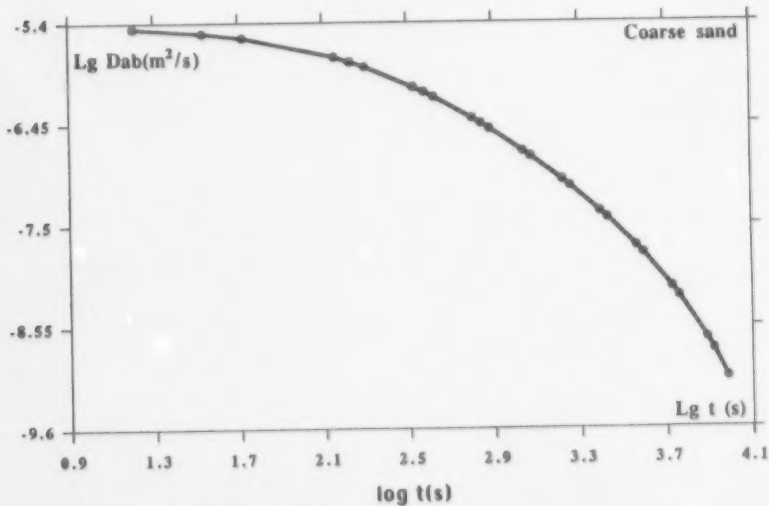


Diagram V.- Plot of diffusivity values against time for evaporated fractions of 0.5 g for gasoline evaporation experiments with coarse sand

Diagram VI to IX shows the variation of N_j against time. Once again one can observe that the mass transference is much higher at the very beginning of the evaporation process because of the higher concentration of volatile components the steep and gentle sloper show you that the transference is not a continuous process, since the evaporation process is influenced by variation in air velocity, its temperature and be solar radiation.

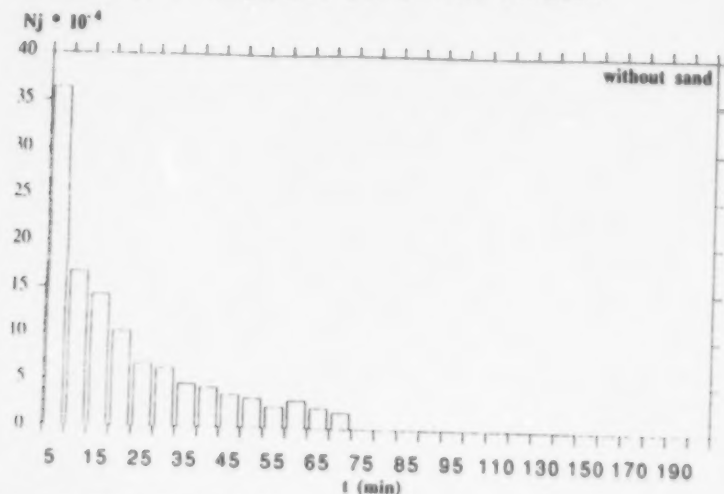


Diagram VI.- Plot of N_j values against time for evaporated fractions of 0.5 g for gasoline evaporation experiments without sand.

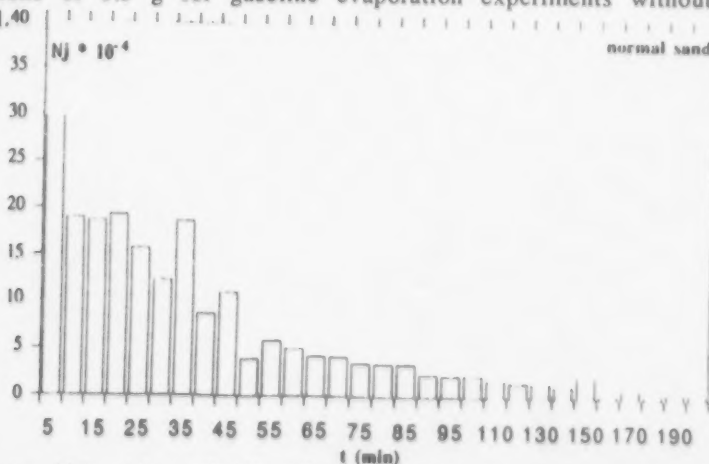


Diagram VII.- Plot of N_j values against time for evaporated fractions of 0.5 g for gasoline evaporation experiments with normal sand

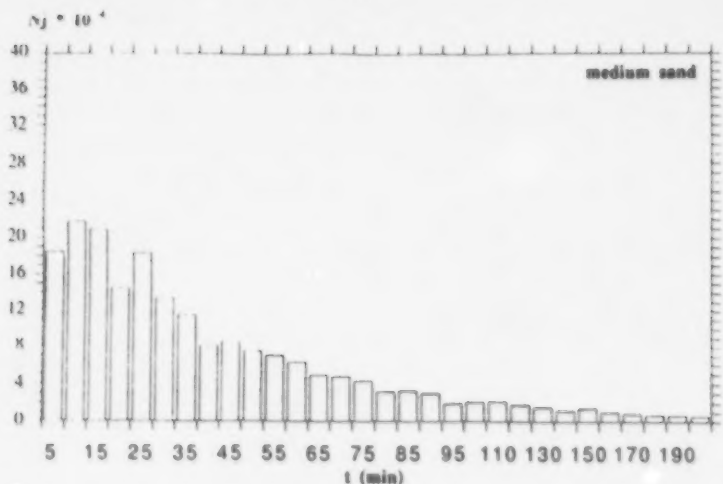


Diagram VIII.- Plot of N_j values against time for evaporated fractions of 0.5 g for gasoline evaporation experiments with medium sand

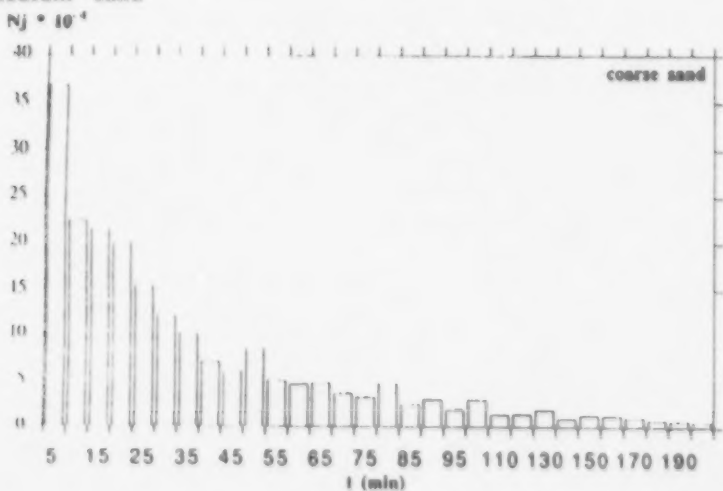


Diagram IX.- Plot of N_j values against time for evaporated fractions of 0.5 g for gasoline evaporation experiments with coarse sand

4.- Conclusions.

- 1) The suggested equation ($F_m = a \cdot \ln(1 + b \cdot t)$) in order to correlate the fraction of evaporated mass to the factor

time has proved to be the correct one to understand the evaporation process, not only through the carried-out laboratory experiments but also by those which had taken place in the natural environment.

- 2) With regards to the carried-out experiments on sand, one can conclude that the value for the parameter a increase with the decreasing sand-particle size, therefore, this parameter in some way or another, measures the level of evaporation resistance. This can be verified by comparing the values for a obtained from the experiments without sand with those obtained from large-sized sand. Both values are similar.
- 3) The parameter b decrease in the experiments without sand in contrast with those carried out on sand, although it hardly varies in relation to the particle size. This parameter is influenced by the increase or decrease in the mass transference surface.
- 4) The different reactions of the spilled gasoline without sand or on sand is conditioned by the liquid-liquid interaction in the former and by the liquid-liquid and solid-liquid interaction in the latter one. In the sand experiment the liquid entirely wets the solid surface and so increases its transference surface with regards to gasoline spilled without any sand. This in turn leads to an increase in both the N_j and the diffusivity since the interaction between the sand surface and gasoline molecule is different from the interaction between only gasoline molecules. The capillary phenomena which takes place when gasoline is spilled on sand also contributes to the increase of the before-mentioned values. Diagrams II to V show how sand, which has different textures and therefore a different surface, influences in a different way the process of substance transference.

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THE LATEST OIL SPILLS IN THE MEDITERRANEAN SEA

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The shipping of crude oil and its derived products is fundamental due to the separate locations of oil producing countries and consumer markets. Shipping is usually carried out by large draught vessels and any accident which involves large volume oil spills may result ecological and environmental disasters. It is estimated that a 75% of all the factors which cause crude-oil spills are contributed to human errors and its remaining part to technical faults and others. A reduction in the overall pollution may be obtained through personnel training schemes, improvements in equipment and cleaning procedures.

Crude-oil spills at sea are usually produced during the loading and unloading of oil tankers and its ballasting, etc. However, oil crude escapes from off-shore and land oil-explotation rigs should also be taken into account. The before-mentioned factors in terms of volume and its coastal location are often highlighted in the mass media and in society as a whole.

However, despite its importance; it is estimated that these spills are of little importance in the overall pollution of seas and oceans taken over a year (Diagram I).

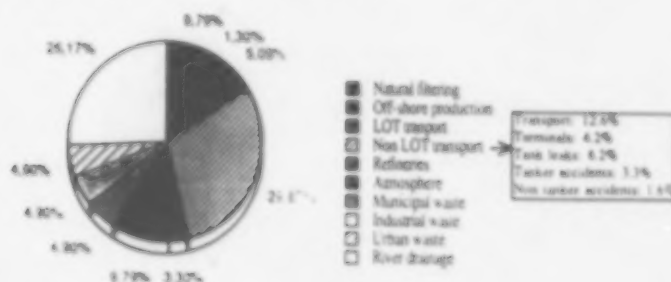


Diagram I.-Annual amount and source of hydrocarbons into the sea.

The estimated volume of crude-oil spills and its evolution in 1970, 1980 and 1990 are shown in Diagram II.

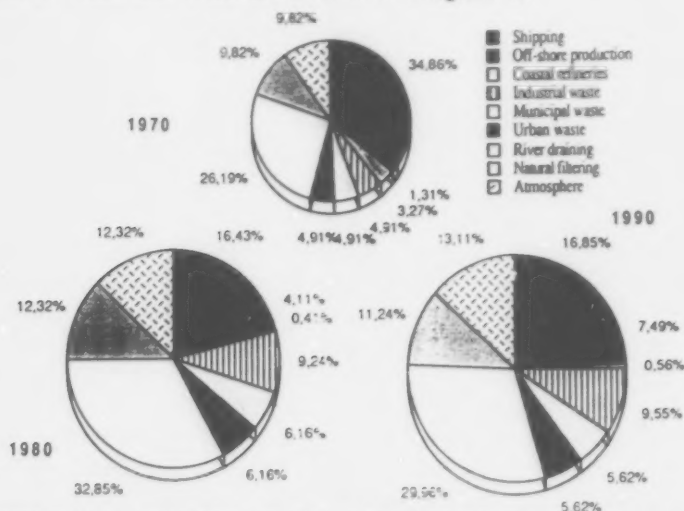


Diagram II.- Evaluation of the annual amounts and sources of hydrocarbons received by the sea.

Crude-oil spills at sea between 1974 and 1985 per tanker accident were mainly caused by vessels inferior to 7 metric tons (Diagram III).

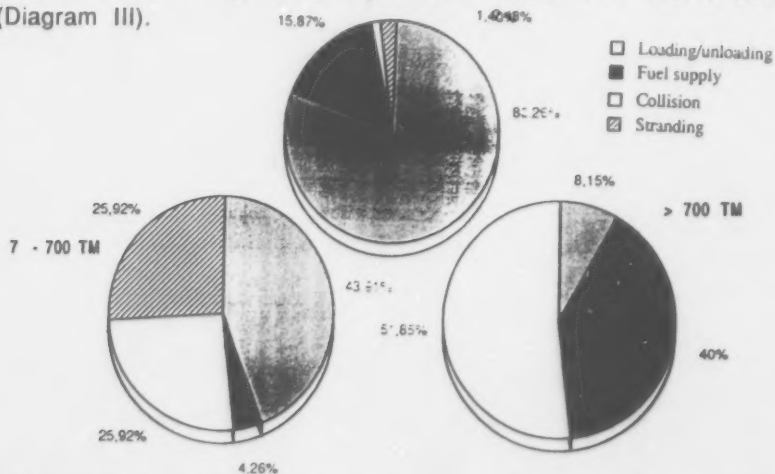


Diagram III.- Volumes spilled into the sea between 1974 and 1985 and its relation with the tonnage of ships.

As the marine ecological system is one of the most important food production resources of today and essential in the near future not only research into sea pollution and its causes but also concerning; cleaning strategies and procedures should be considered as of utmost priority.

THE "AGIP ABRUZZO" OIL TANKER SPILL.

On the 10th of April the first oil-spill in the Mediterranean took place when the ferry "Moby Prince" from Livorno (Italy) (see number one of Diagram IV) to Olbia (Sardinia) collided with the oil tanker "Agip Abruzzo". The former, which started burning later on, was loaded with 82000 metric tons of Iranian crude-oil being moored off at 2 km from the port outlet and awaited unloading. Due to the collision, a 3000 metric tons crude-oil spill was produced and another 12000 metric tons was burning. The produced oil spill had little impact on the sea environment as the greater part of the spilled crude-oil was removed. Air pollution produced by the released gases from the 12000 metric tons burning crude-oil was considered as of little or no importance.

However, a 140 people (crew and passengers from the ferry) were killed in the accident, only one of whom escaped alive.



Diagram IV.- Areas affected by spills.

THE CYPREN "HAVEN" OIL-TANKER ACCIDENT.

The Cypren "HAVEN" oil-tanker accident occurred on the 11th of April at 12.45 hrs. The first explosion with fire breaking out took place later on. This vessel was the twin ship of the "Amoco Cadiz" which was damaged in accident at the Port Sall reefs on the night of the 16th and 17th of March 1978.

The oil-tanker had just unloaded 80000 tons of crude oil at the oil-terminal of Arenzano when the accident happened (see number 2 of Diagram IV). Consequently a 3000 metric-ton crude-oil spill covering a surface of 25 km² and polluting the Liguria coast was produced.

On the 13th of April a second explosion with fire breaking out occurred. The 100 metre high black clouds of smoke polluted the entire Genova area. After some time, the ship partially sunk at 15 miles to the south Arenzano in westward direction of Genova and continued burning for 70 hrs. The Italian authorities decided to tow the burning ship towards more shallow waters to the west of Genova in order to reduce the ecological impact on the environment. A third explosion at 5.30 AM on the 14th of April caused a new oil spill. In total about nine different explosions had occurred until the ship finally sunk at 44° 03' 22" degrees north and 08° 1' 42" degrees east at 10.05 am on the 14th of April and settled down on a sand bank at 60 metres below sea level (see number 3 Diagram IV). No crude-oil escape from the sunken ship has been observed. According to the most recent inspections four of the lateral oil-tanks were open from above and probably didn't contain any crude at all. The next tasks were aimed at removing the crude-oil still present in its other deposits in order to avoid possible oil spills because of its future deterioration.

In order to remove the large crude-oil flood the following cleaning procedures have been carried out:

1.- Cleaning procedures at sea.

A large number of means ranging from supplying ships to the so-called "Pelicano" skimmers have been used in removing the crude-oil. Through these means 1786 m³ of crude-oil equivalent to 3500 m³ crude-oil-water mixtures had been collected until the 17 of April. On that same day works at sea were interrupted because of bad weather conditions. Consequently the floating crude-oil was dispersed on the sea surface, and after some days

large-scale cleaning procedures were stopped and just two units to remove the crude-oil escaping from the wreck were in use. Except for the continuous escapes (from 1 to 4 m³/hour) the total spilled volume of crude-oil was practically removed from the sea surface, although some was washed ashore. Owing to the escapes from the wreck the routine cleaning operations had to be continued in order to remove these smaller quantities of spilled crude-oil. When the burnt waste approached the French coast, the Italian authorities decided to have it removed. After a second period of bad weather, on the 19th of April 1991, some of the floating patches of crude-oil and same recently spilled crude were also drifting alongside the French coast. Except for the continuous escapes from the wrecked off ship and washed-away waste from the coast no other crude-oil spills were observed on the sea surface.

2.- Coastal cleaning operations.

The most heavily polluted coastal areas were the ones near Varazze, Cogoletto and Arenzano (see number 4; 5; 6 of Diagram IV). The cleaning operations to remove the crude-oil in the coastal areas were carried out by military servicemen, and skilled labour equipped with trucks, motorpumps, bulldozers and other means to build the corresponding roads.

The situation was daily evaluated by the Taskforce and daily reports were given by admiral Agrinsano. Besides several meetings with the local authorities to explain the present situation. Conferences on cleaning procedures of crude-oil removal of the sea and coast were given to the inhabitants and to the authorities of the coastal villages.

The collected crude-oil was stored in jerry cans, containers and plastic bags. 200 jerry cans and 84 small and big containers were distributed. On the 30th of April. About 300 m³ of solid crude and crude-oil containing solid components had been gathered and was temporarily stored at Voltry.

Some of the crude-oil filtered through the beach sand up to depth of 10 to 20 cm and its cleaning took much more time. To protect the polluted coast, floating cushions were used but due to the occurrence of winds, sometimes at gale force (Beaufort 7) most of them were damaged. On the 20th of April, about 1786 m³ of crude-oil had been collected at the terminal of Miltedo as well as

60 m³ was collected by trucks and stored at Albisona. The crude-oil was recycled at the terminal and the solid waste was treated in a blast furnace. Every afternoon new recommendations for the following days were given by the I.T.O.F. and by admiral Angrisano under the direction of admiral Alati.

According to the latest information (1) the ecological impact produced by the oil-tankers "Haven" was considered as of little or no importance because of the following factors:

- 1) The spell of good weather during the first days which allowed removal of the floating crude-oil from the sea surface.
- 2) Some of the crude-oil was burnt during the 70 hour long fire. Consequently the residual consisting of semi-solid components produced by combustions didn't disperse over the sea-surface.
- 3) The amount of crude oil released by the oil-tanker was restricted.
- 4) Our research has shown that this type of crude-oil can evaporate up to a 35% (5).
- 5) Owing to bad weather conditions on the 17th and 18th of April the rate of natural dispersion of the remaining crude-oil floating on the sea surface (part of which was evaporated and removed) was considered as very high.
- 6) The remaining parts of the burnt crude was washed ashore in small quantities and could be removed manually.

From the 20th of April onwards the cleaning operations at sea as well as on the coast were merely routine procedures and they mainly consisted of:

- 1) Observing through daily air vigilance the presence of crude-oil.
- 2) When weather conditions allowed, one or two standby ship removed the crude-oil.
- 3) New crude-oil escapes were limited to a minimum.
- 4) The remaining crude-oil polluting the wasted areas was continuously removed.
- 5) The cleaning of polluted ships.

As a result of the explosions and burning of 17000 tons of crude-oil toxic clouds containing crude-oil particles from its incomplete combustions, sulphur dioxide as well as nitrogen oxigen blocked the sun beams in the affected area and provoked acid rains.

The effects of the floating crude-oil on fish life are among others, the direct poisoning through ingestion of emulsified hydrocarbons, of animals, of polluted plant life as well as causing obstruction of the gills.

Bird life has been affected in various ways. Not only has it led to toxic effects through ingestion of polluted organisms but also through direct ingestion of crude-oil when bird tried to remove it from their feathers. On the other hand the crude-oil covered feathers neutralized their impermeability and this has led to a loss of their thermic isolation.

The "Haven" oil-tanker displaced 232163 metric tons deadweight and its cargo was distributed in 16 lateral and 4 central tanks. When the accident occurred a cargo of 143000 metric tons of heavy Iranian crude-oil of the following characteristics was shipped:

Density	30.8 °API
Viscosity (100 °F)	9.81 cSt
Steam pressure Reid (PVR)	6.6 Psi
Pour point	15 °C
Sulphur	1.5 % w,w
Remaining carbon	5.0 % w,w
Propane	0.5 ppm
Isobutane	0.3 ppm
Butane	1.2 ppm
Vanadium	88 ppm
Nickel	30 ppm
Ethane	0.1 % v,v

THE EXPERIMENTAL STAGE.

The writers of this paper in collaboration with the State Government Delegation of the Balearic Islands (i.e. the Civil Protection Service) have analysed the crude-oil residuals drifting

alongside the Balearic coast in order to find out whether these remains proceeded from the "Haven" oil-tanker or not.

A total of 15 samples were analysed. The first sample was taken by Mr. A. Javier Guillen Pinacho about two miles from cape Ferruch on the 30th of May of 1991 (see number 7 of Diagram IV) and contained semi-solid components although it didn't correspond with the chocolate mousse emulsion type. The other samples were taken by one of the writers of this research paper (i.e. J.R. Bergueiro) on the 15th of July of 1991 on the El Arenal beach (Palma bay, Spain, see number 8 of Diagram IV) and contained semi-solid components with higher viscosity than the first sample.

The carried out analysis.

The presence in a quantitative and qualitative way of hydro-carbon in the samples were determined with fractions of the samples dissolved in hexano and its analysis was carried out through the system of Gas Chromatography. In these experiment a gas chromatograph called the Perkin Elmer Sigma 3B was used and connected to a data base Perkin Elmer Sigma 10. The characteristics of the used column and programme were the following:

Column: OW 101 (2 metres long and 1/8 inch wide, CH. W. HP. 80/100 Mesh)

Programme:

Gas carrier N ₂	
Velocity of gas carrier:	20 mL/min.
Initial temperatura:	80°C
Temperatura interval:	8°C/min
Final temperatura:	250°C
Time consumed:	15 min.
Temperature of inyector:	250°C
Temperature of detector:	265°C

The used crude-oil standards were supplied by the United States Environmental Protection Agency (Environmental Monitoring and Support Laboratory).

The analysis through the gas chromatography system of the fractions solubles in hexane, showed that in the first sample, volatile hydro-carbons ranging from undecane, dodecane, tridecane, etc, even C₂₅ including their isomeric compound

remains were present. The other samples indicated the presence of nonane, decane, undecane, dodecane, etc, even C_{25} together with its isomers.

Estimating that the fifteen analysed residual sample could proceed from the "Haven" spill a number of experiments with similar heavy Iranian crude-oil as was shipped by the "Haven" tanker was carried out, since it was impossible to obtain a sample of the crude oil from this tanker.

On the one hand experiments were aimed at determining the evaporated fraction of heavy Iranian crude-oil in function of the factor time when being spilled on sea water or on different-sized beach sand and comparing these samples with those found at sea or on the beach. The procedure of establishing the evaporation process consisted in passing an air current at a determined velocity and temperature over a board on which the crude-oil to be evaporated was placed (useful board surface 73.44 cm^2). At certain intervals the current of air was interrupted and owing to difference in weight the evaporated fraction in function of time was determined. Through the following equation its fraction can be related to the span of time consumed during the evaporation process:

$$F_m = a \cdot \ln(1 + b \cdot t)$$

whereby:

F_m = evaporated fraction in mass

t = time consumed during the evaporation process.

a and b = parameters to be determined through the fitting.

In order to be able to correlate the findings of the experiments on evaporated fraction in function of time the Marquardt method has been used (2).

Diagram V shows the effects of the air velocity on parameters a and b of heavy Iranian crude evaporation curve at 15°C and 25°C with air velocities of 0.2; 1.0; 2.5; 3.9 and 5.8 m/s.

The evaporation of spilled crude-oil on beach sand was included in the research in case the "Haven" crude-oil would pollute the Balearic Islands, which in turn would make it possible to reduce it or to decide as which cleaning procedures for the polluted beaches would have been the most suitable one. Therefore the before mentioned experiments were repeated in order to determine the variation in evaporated fractions spilled on limestone beach sand of the Balearic Island. Given the fact that the sand texture varies from one beach to the other three types of

sand obtained through sieving, once pebbles, shells and other large-size particles as well as its dust fraction (at low proportions) were removed, were used in the experiments. The three types of research sand were: normal beach sand (without sieving); coarse sand (the particles of which had a diameter ranging from 0.5 to 1.0 mm) and medium-sized sand with particles ranging from 0.25 to 0.5 mm in diameter.

The experiments were carried out with 150 g of sand placed on 73.44 cm² sized boards and 40 g of heavy Iranian crude-oil. A current of air at temperatures similar to the pre-heated board was directed over its surface. The selected temperatures were 15 and 25°C degrees Celsius with air velocities of 0.2; 1.0; 2.5; 3.9 and 5.8 m/s.

Diagrams V; VI; VII and VIII will show you the findings of the parameters a and b obtained through the Marquardt fitting procedure with spilled crude-oil on beach sand at temperature of 15 and 25°C degrees Celsius.

More details on this research stage can be obtained from research papers (3; 4; 5; 6 and 7) carried out by the same researchers.

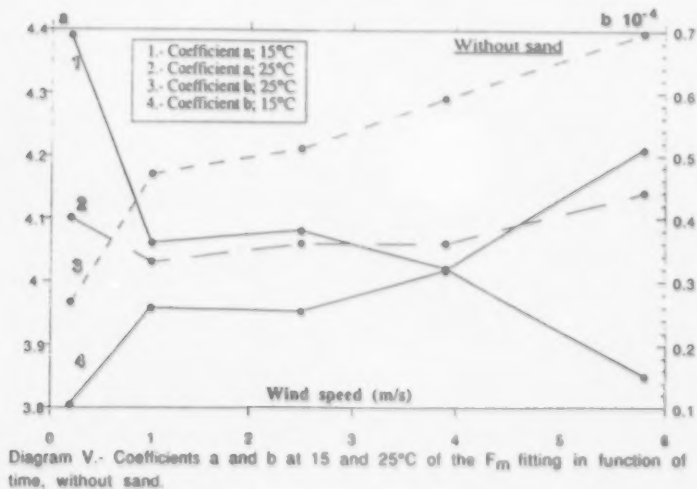


Diagram V.- Coefficients a and b at 15 and 25°C of the F_m fitting in function of time, without sand.

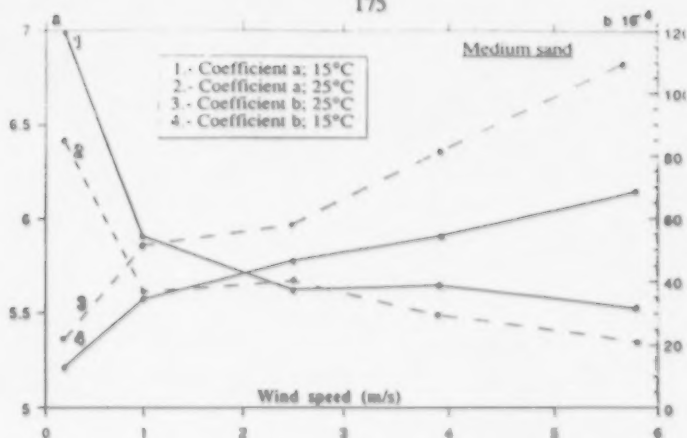


Diagram VI.- Coefficients a and b at 15 and 25°C of the F_m fitting in function of time, medium sand.

Diagram VI.- Coefficients a and b at 15 and 25°C of the F_m fitting in function of time, medium sand.

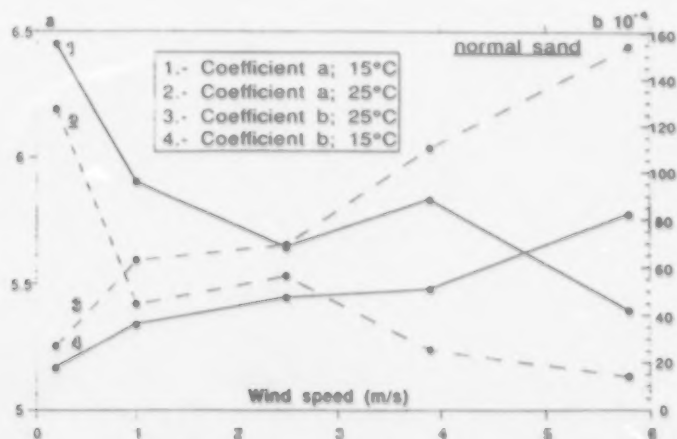


Diagram VII.- Coefficients a and b at 15 and 25°C of the F_m fitting in function of time, normal sand.

Diagram VII.- Coefficients a and b at 15 and 25°C of the F_m fitting in function of time, normal sand.

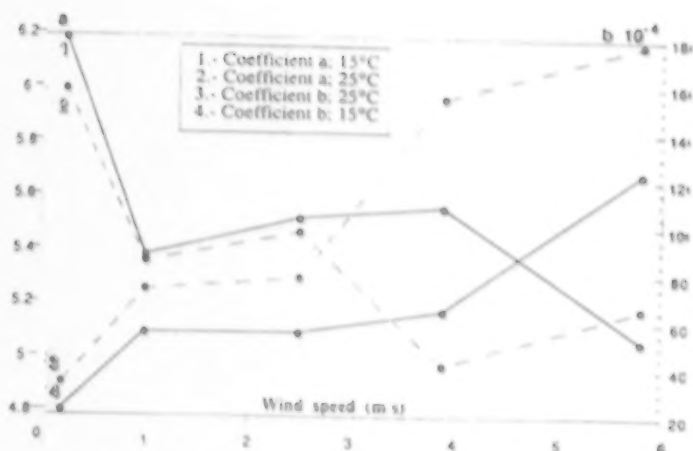


Diagram VIII.- Coefficients a and b at 15 and 25°C of the F_m fitting in function of time, coarse sand.

Diagram VIII.- Coefficients a and b at 15 and 25°C of the F_m fitting in function of time, coarse sand.

Considering the possibility that the "Haven" crude-oil would pollute the beaches of the Balearic Islands research on the Retention Capacity, the Filtered Volume and the Absorbed Amount in beach sand of the same texture with spilled heavy Iranian crude-oil has been carried out. Diagram IX shows the variation in infiltrated and retained volume of gasoline in function of the type of sand used in the experiment.

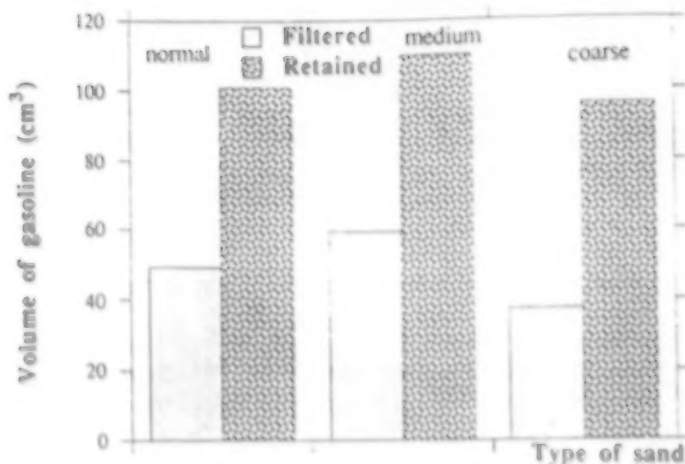


Diagram IX.- Variation in volume of infiltrated and retained gasoline according to type of sand.

The effects of the type of sand on the retention capacity of a heavy Iranian crude-oil is shown in Table I.

Type of sand	Volume of sand (cc.)	Retention capacity (L crude-oil/m ³ sand)
Normal	400	252.50
Medium	400	275.00
Coarse	400	240.00

Table I. Effects of the type of sand on the retention capacity of heavy Iranian crude-oil.

More details on the applied procedures can be obtained from research papers 5 and 6 written by the same authors.

On the other hand dissolved fractions in the remaining hexane mixtures at different values of F_m of the crude oil used in carrying out the experiments were analysed with the whithe of the gas chromatograph method. It was observed that hydrocarbons such as nonane, decane and undecane had disappeared after 36 hours. The pour point (the lowest temperature at which a substance, such as oil, will flow under specific conditions) of the heavy Iranian crude-oil (which -6°C) was higher compared to the sea and air temperatures at the time of the crude-oil spilling.

Consequently, the crude-oil continued dispersing itself. This phenomenon as well as bad weather conditions after the oil spill helped in evaporating its volatile components. On the other hand these conditions also made the formation of certain solid masses difficult and considerably slowed down the diffusion process towards the surface, particularly the volatile components which were not released from its interior and so delayed its corresponding evaporation.

According to Kinney (8) hydrocarbons less than size of 12 carbons atoms are evaporated during the first 8 hours after any spill under reasonable temperature and air velocity conditions. Carsin (9) based on his research into the Amoco Cadiz spill concluded that a 50% of the crude-oil spilled weight could disappear from the sea surface within a few days and a 75% in weight during a period of three weeks. In our case in a similar way the total amount of hydrocarbons inferior to C₁₂ had practically disappeared with six days and those inferior to C₁₆ within 10 days.

Given the span of time passed when the accident happened and the sample-taking and considering the experiments described before we can conclude that if the analysed samples proceeded from the "Haven" spill, they must have undergone a relatively long weathering-out process (much higher than described in our sample analysis) and for that research no hydrocarbon inferior to C₁₆ were detected. Prior to the 30th May (date of first sample taking) nothing was known about crude-oil from the "Haven" spill drifting alongside the Balearic Island as well as The Spanish Levant Coast. Therefore we have drawn the conclusion that the analysed samples couldn't proceed from the before mentioned "Haven" spill.

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**NATURAL RESOURCE DAMAGE
ASSESSMENTS FOR OIL SPILLS:
STATUS OF RULES AND
APPLICATION TO RECENT OIL SPILLS**

by

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INTRODUCTION

Oil, whether it is crude oil, bunker oil or some refined product in between, will usually cause adverse effects to natural resources, primarily biota, surface water and surface sediments, when the oil is released to the natural environment. The spilled oil may also directly or indirectly affect people's use of these natural resources, as well as their use and enjoyment of the environment as a whole. These effects of the spilled oil begin when the oil is first released, continue through cleanup activities, and often extend beyond the active cleanup process until the resources and environment are restored, naturally or with human intervention, to some acceptable *baseline or reference condition*.

In the United States, the economic value of these effects and the costs of restoration as they relate to natural resources under the jurisdiction and management of government agencies or Indian tribes may be collected from the person or entity responsible for the spill by the agencies or tribes. These economic values and costs may be determined in the Natural Resources Damage Assessment (NRDA) process. The use of the NRDA process for oil spills is authorized albeit not required by the federal Clean Water Act and more recently the Oil Pollution Act of 1990 (OPA 1990). The procedures are described in rules prepared by the U.S. Department of

Interior (DOI) and in preparation by the National Oceanic and Atmospheric Administration (NOAA) in the U.S. Department of Commerce.

NRDAs are also applicable to (a) spills of chemicals and hazardous materials other than oil, (b) hazardous waste sites being cleaned up under the general rubric of "Superfund" and (c) sites where hazardous materials are alleged by trustees to have resulted in injury to natural resources. These applications of the NRDA are similar to that for oil spills, though there may be significant differences in the specifics.

This paper summarizes the NRDA process as it applies to oil spills, its present (mid-1992) status, and its application to several recent spills.

WHAT IS AN NRDA? CONCEPT AND DEFINITIONS

The NRDA is based on the concept that all natural resources that are managed by government agencies or Indian tribes (*trustees*) are available to the public for its use and enjoyment. That is, these natural resources, provide to the public *use services* such as fishing, birdwatching, surfing and research opportunities, and *non-use services* such as the opportunity to use a resource, even if such a use is not presently planned. These services have an economic value to people. The loss or reduction (*foregone use*) of these services caused by an oil spill due to effects (or *injury*) to the natural resources, results in a reduction of that economic value (i.e., *damages*). The spiller or potentially responsible party (PRP) is responsible to the public, through the trustees to make the public whole by paying damages for the foregone services, for *restoration* to the point services are restored to some pre-determined baseline or reference condition, and for the trustees' costs of conducting the NRDA. The trustee(s) are responsible for applying all the damages (money) recovered to the restoration of foregone services and natural resources, and to their assessment costs.

Natural resources are liberally defined as *surface water, ground water, air, geologic and biological resources* "...belonging to, managed by, held in trust by, appertaining to, or otherwise controlled by the United States..., any State or local government, any Indian tribe..." People and natural resources solely in the ownership of a private party are about the only resources not included in the definition.

Restoration is broadly defined as "...actions undertaken to return an injured natural resource to its baseline condition, as measured in terms of the injured resource's physical, chemical or biological properties or the services it previously provided..." Restoration alternatives include no-action (i.e. natural recovery), active restoration, rehabilitation, replacement and/or acquisition of the equivalent resources and related lost services. To date, there is little experience to determine what restoration really means in the NRDA context, though there have been several large damage settlements and NOAA has established a group within the National Marine Fisheries Service (NMFS) to evaluate and develop restoration methods.

The NRDA, then, is the process by which the injuries to natural resources caused by the spilled oil are determined, the loss of services provided by these injured natural resources is quantified, and the economic value of these foregone services is determined. In addition, the NRDA process should determine the appropriate means of restoring the foregone services and provide a cost for doing so. These values plus the cost of conducting the NRDA are combined as the compensable damages due to the trustees from the PRP. Finally, the NRDA process should implement the appropriate restoration activities.

WHAT IS THE LEGAL AND REGULATORY AUTHORITY BEHIND AN NRDA?

In the United States, the concept of damages or compensation for injury to natural resources from releases of oil, chemicals, and other hazardous materials was given legislative authority in the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA) and the Clean Water Act. Promulgation of rules describing NRDA procedures and protocols were delegated to the DOI. The final Type B procedures were published in Federal Register on August 1, 1986 and final Type A procedures on March 20, 1987. There have been several legal challenges to these rules and a number of revisions have been proposed as a result. The details are not critical here, and the reader is referred to Federal Register of April 29, 1991 for a synopsis of the status of the rules. What is important to PRPs is that there is an extant law, with supporting rules, that implements the NRDA process in the United States.

A third law, the Oil Pollution Act of 1990, provides for compensation for natural resource damages resulting from oil spills. OPA 1990 also provides for NOAA to develop the rules for the NRDA procedures. When they are promulgated, NOAA's rules will apply only to oil spills and DOI's rules will apply to chemical spills and other releases of hazardous materials. There are other differences between the laws and there will likely be some differences between the rules. However, NOAA does not expect to publish the draft rules until late 1992 at the earliest.

Most coastal states including Washington, Florida, Alaska, Texas, California and several inland states have an NRDA process that often may be less complex but still results in substantial damages for injuries resulting from oil spills. These laws change frequently. There are several reference sources to keep track of the state (and federal) laws and they are updated on a regular (at least monthly) basis.

We are not aware of similar promulgated NRDA laws or rules in other countries, provinces or states. However, various trustee agencies, industry representatives and environmental scientists have indicated that various government agencies are evaluating the establishment of an NRDA process in some form.

To date (mid-1992), the application of the NRDA process to an oil spill or the settlement resulting from the process has not been tested in the U.S. court system. There is essentially no case law or precedent to determine if the NRDA process is valid, fair, or legally defensible as it applies to oil spills. Therefore, PRPs may be well-advised to use the NRDA rules as a guide to assessing injury, potential damages and restoration alternatives related to an oil spill, on the assumption that the trustees will also generally follow the rules and these rules will carry some authority if the trustees' claims are challenged in court by the PRPs.

WHY SHOULD THE OIL SPILL PRP BE CONCERNED ABOUT NRDA?

There are at least four reasons that PRPs should be aware of and concerned about NRDA's in the context of oil spills. First, there are federal laws in the United States that allow for the application of an NRDA to an oil spill and there are rules that describe the process in detail. Some parts of the rules are in the process of being revised, and new rules are being prepared by NOAA, specifically for oil spills.

These rules give the trustees substantial authority to assess and collect natural resource damages (NRD) from PRPs.

Second, the damage sums are substantial, even for relatively small oil spills. For example, the NRD for the Shell Martinez oil spill were about \$11 million, for the Exxon Bayway oil spill about \$10 million, and for the Exxon Valdez about \$900 million. In addition, there are substantial study or transaction costs which may equal 10-50% of the damages assessed. These transaction costs include both (a) the PRP's costs for technical studies plus legal and internal costs to obtain data to defend itself in negotiations and/or litigation with the trustees, and (b) costs reimbursable to the trustees for their assessment activities.

Third, the trustees are becoming more aware of the potential for large damage settlements that can be obtained from NRDA's. The nearly \$11 million NRD settlement from the 1988 Shell Oil Martinez Refinery oil spill was probably the precedent for many subsequent large settlements. The \$900 million to \$1 billion settlement (depending upon how the damages are allocated) for the Exxon Valdez NRDA is the largest to date. However, there are several other NRDA's in progress that, might settle for tens of millions of dollars.

Fourth, several states (e.g., Washington and Florida) have promulgated NRDA laws and rules that are different than the federal ones, and other states are considering NRDA laws. In addition, other governments such as Canada and British Columbia are evaluating promulgation of NRDA laws and rules that may (or may not) be similar to the United States federal and/or state laws. It is in the PRPs' interest to be aware of these legislative and regulatory developments which may influence the means and cost of doing business within the trustees' jurisdictions.

HOW IS THE NRDA IMPLEMENTED?

The DOI regulations describe two procedures, Type A and Type B, for implementing an NRDA (Figure 1). The Type A procedure, or natural resource damage assessment model (NRDAM) is a computer model that requires several specific but easily obtained input values and it then generates a damage value for the oil spill. There is presently only a model for the coastal and marine environment (CME) though a Great Lakes model is in the final stages of

NATURAL RESOURCE DAMAGE ASSESSMENT RULE 43 CFR PART 11

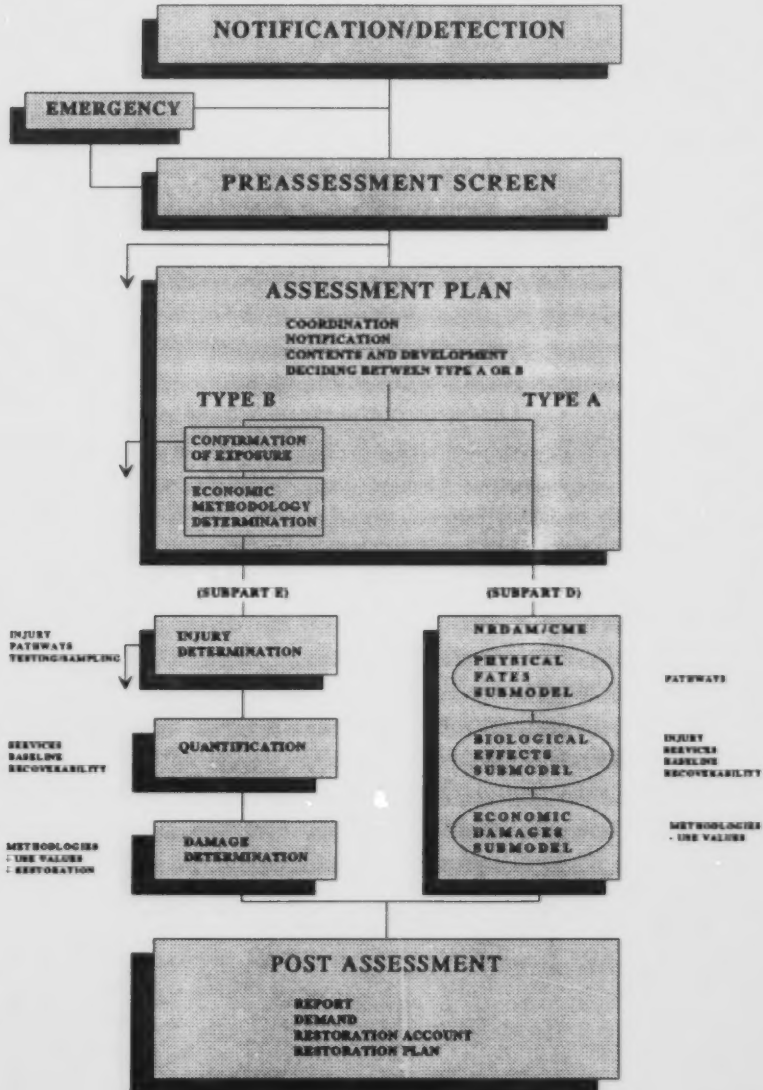


Figure 1. The Four Phases in a Natural Resource Damage Assessment

Trustees, as indicated in the previous paragraph, are primarily federal and state government agencies and Indian tribes that manage the natural resources for the public. Under OPA 1980, trustees will also include foreign governments and, in certain circumstances, individuals. Obviously, given the broad definition of natural resources and the overlapping management responsibilities between and among state and/or federal agencies for managing these resources, there could be (and usually are) overlapping and competing demands by trustees for the lead responsibility in the NRDA process.

Services are the physical and biological functions performed by the resource, including the human use of these functions. Services are the result of physical, chemical or biological quality of the resource. *Use services* are those which are provided directly to humans. Thus a valid economic value can usually be assigned to these services (e.g. fishing, bird watching, beach combing). *Non-use services*, often called *intrinsic* values, *bequest* values, and a variety of similar terms, are those which may not be provided directly to humans and thus it is much more difficult to assign a valid economic value to these services (e.g. value of services a wetland provides to people by virtue of being habitat for the endangered, but rarely seen, saltmarsh harvest mouse, or the value of knowing the Grand Canyon exists whether or not one plans to ever actually visit the site).

Injury is "...a measurable, adverse change, either long- or short-term, in the chemical or physical quality or the viability of a natural resource resulting either directly or indirectly from exposure to a discharge of oil..." The NRDA process requires that the pathway from the spilled oil to the injuries (for which there are explicit criteria in the DOI regulations) be demonstrable and documented, and not merely speculation. In the more traditional environmental impact assessment process, injuries would be called probable and/or documented *impacts*.

Damages is the amount of money sought by the trustee(s) to compensate for foregone services resulting from injuries caused by the oil spill, restoration of the services, and the trustees' additional costs of conducting the NRDA. The law and regulations are explicit that the natural resource damage amount does *not* include fines, penalties, "outrage" factor, or any other punitive measures; there are other avenues for assessing and obtaining these monies. The laws and rules are also clear that the damages are to be used only for restoration of the services and injured natural resources.

development by DOI. The Type A model is a simplified procedure that was intended for use generally in small spills where there were few highly sensitive natural resources and where the injury and damage assessment would probably not be controversial. As might be expected, few oil spills meet these criteria (at least in the view of the trustees and/or the public), so the Type A procedure has not been applied very often.

The Type B procedure is a more thorough and complicated one that involves a number of phases and steps within the phases (Figure 1). The full Type B procedure for a major oil spill in a sensitive area could involve a multi-year program including extensive field sampling, data collection and analysis, and detailed evaluation of restoration alternatives. The Type B procedure generally takes substantial time and money to initiate and implement. The DOI rules published in Federal Register on August 1, 1986 provide a detailed description of the procedures shown in Figure 1. The proposed rule published on April 29, 1991 in Federal Register describes the proposed changes to the rule, primarily to the Type B procedures.

NOAA has indicated in the Advanced Notice of Proposed Rulemaking published in Federal Register on March 13, 1992 that they may retain the Type A and Type B procedures, and are considering adding two other procedures. One is a "compensation table" which is envisioned as a simplified form of the Type A model. That is, values for several variables including some related specifically to the type and amount of natural resources affected would be entered into a formula or table, and this would produce a damage figure. Though the concept may be attractive to both trustees and PRPs, the actual development and use of these compensation tables may meet with the same challenges and problems the Type A models have. At least two states, Washington and Florida, have developed compensation tables or formulae which are now part of the states' statutes. However, they have not been used to date (May 1992) so there is no experience with their application or acceptance of the results.

The second procedure NOAA is considering is an Expedited Damage Assessment (EDA) which is essentially an expedited Type B. [Incidentally, NOAA has referred to the Type B assessment as a Comprehensive Damage Assessment or CDA.] The procedures for conducting an EDA have not been published by NOAA; however, the general approach probably would be to rely to a large extent on existing

information to conduct the injury determination and services quantification steps of the Assessment Plan, rather than collecting substantial site- and spill-specific data.

Having described the existing or proposed procedures, we caution the PRPs that the trustees, including those in the Department of Interior (e.g., U.S. Fish and Wildlife Service), are not required to use all or any part of the rules to conduct the NRDA. Furthermore, the regulations are federal ones and the states are not obligated to follow the federal rules at all. Both federal and state trustees may use whatever procedures they choose. To date, most trustees have taken a selective approach to using the DOI rules, selecting some elements and rejecting or modifying others. However, the elements that are accepted, rejected and/or modified have not been consistent so it is difficult for a PRP to determine how the trustees are likely to implement the NRDA for a specific spill.

WHAT IS THE NRDA EXPERIENCE IN OIL SPILLS TO DATE?

Monetary compensation or damages for injury to natural resources has been a feature of oil spills since the Union Oil Platform blowout in Santa Barbara in 1969 and the T/V *Zoe Colocotroni* spill near mangroves in Puerto Rico in 1973. Damages were collected, primarily for birds and recreational uses in the Santa Barbara spill. However, in the *Zoe Colocotroni* spill, the majority of damages claimed for loss of barnacles and other organisms were not collected. The procedure for evaluating the damages and the application of the damages to restoration of natural resources began to receive more attention as a result of the settlements in these spills.

In the T/V *Puerto Rican* spill, offshore of San Francisco, California in 1984, damages were claimed for birds, fish, and plankton (using crab larvae as a proxy for all plankton). However, the trustees were only able to demonstrate and document injury to and thus settle for damages for oiled seabirds. The procedures for placing an economic value on the services provided by the birds were not made public, but they appear to resemble the NRDA procedures that were published in 1986.

To our knowledge, there have been few applications of the Type A NRDAM/CME to oil spills where the damages calculated by the model were accepted by the

trustees and the PRPs as a fair value. It has been used in several instances to provide a dollar value that then served as a starting point for negotiations between the trustees and PRPs regarding a damage settlement. Therefore, in the future, one might expect that the Type A model in its existing form or possibly even in its modified forms (to be released sometime in late 1992 or 1993 according to DOI) will be used mostly to initiate settlement discussions. The exceptions may be small, non-controversial oil spills in states which do not have some form of a compensation table or formula.

The 1988 Shell Oil Spill from the Martinez Refinery to Suisun Bay, California, was the first major (400,000 gallon) spill for which the NRDA was conducted by the trustees under the general guidance of the Type B procedures. There were numerous deviations from the published procedure, including a refusal by the trustees to allow Shell Oil Company to participate actively in the process as provided for in the regulations. Trustees in most subsequent major spills have not permitted the PRPs to participate actively in a cooperative NRDA. Nonetheless, the trustees apparently did develop a general approach which then became known generally as the "Shell Model" and has been used by other state and federal trustees.

The "Shell Model" was apparently used by the state trustees in developing the NRDA for the Exxon Bayway Pipeline leak of No.2 fuel oil to Arthur Kill, New York/New Jersey in January 1990. In this settlement, a substantial portion of the damages were to be used to "acquire the equivalent of" injured resources, primarily coastal wetlands to be placed in the public trust.

The T/V *Mega Borg* spill occurred offshore Texas in federal waters. A large amount of oil was spilled, but most of it burned. NOAA, as lead trustee, determined that there was probably no quantifiable loss of services provided by natural resources, and that injury to the natural resources themselves was not likely to be demonstrable or quantifiable. In essence, the trustees determined that damages should be zero. However, they obtained the cooperation and funding of the PRP to conduct studies to demonstrate the validity of this assessment. This was one of, if not the first, instance of a trustee inviting the cooperation of the PRP in conducting the NRDA and other studies in a large oil spill. NOAA and the PRPs hope this cooperative approach becomes the norm rather than the exception in future oil spill NRDA's.

The T/V *Exxon Valdez* oil spill raised the public and trustee awareness about natural resource injury and thus damages. Because the oil spill was such an unusual, large and emotional event, it was difficult for the trustees or Exxon to implement a cooperative NRDA or to improve the development of the NRDA process. However, OPA 1990 was a direct result of the *Exxon Valdez* oil spill and this legislation provided for NOAA to develop NRDA procedures that are specific to oil spills. NOAA has the opportunity and is working diligently to modify the model provided by the DOI regulations so they are more effective for oil spills. In addition, the trustees' and PRPs' knowledge of restoration alternatives is being and will continue to be substantially improved as a result of the trustees' efforts to determine how to spend several hundred million dollars in "restoration." As mentioned earlier, NMFS has even established a Restoration Group specifically charged with evaluating restoration procedures.

As the NRDA process for each oil spill is completed, the base of experience and information about what works (and doesn't work), as well as how the trustees and PRPs might proceed, expands. There are several ongoing NRDAs, some for large and controversial oil spills, that may set precedents when they are completed and the damage amounts are described in the consent decrees or other settlement documents.

WHAT IS THE FUTURE FOR NRDA?

Beyond saying that we expect NRDAs for oil spills to be a long-standing procedure, we cannot predict with confidence what the future holds for NRDAs. However, we can speculate about some possibilities.

Assuming that there are several moderate to major oil spills over the next few years, there could be a huge sum of money available for "restoration" activities. However, much of this money may remain in trust accounts because (a) multiple trustees may not be able to agree readily on appropriate restoration projects, (b) the trustees may find little to restore as natural recovery will often have accomplished the task first and/or (c) present laws and regulations do not permit the money to be used for research projects to determine what restoration techniques might be appropriate for certain situations. A change in the laws and regulations along with agreement between and among trustees to release the PRPs from all NRD liabilities

once the PRPs pay the damages may allow the trustees more flexibility to apply the funds to a wider variety of "restoration" projects and activities in areas near to and/or far away from the affected area.

We speculate that all parties will recognize that natural recovery is the preferred restoration alternative in almost all oil spills. Mother Nature does the job cheaper and the result is always ecologically acceptable, even if not the one preferred by humans. With this realization, less money would be needed for or spent on active restoration, except possibly for the "acquisition of the equivalent of" natural resources to be placed in the public trust. However, natural recovery for some resources, such as some wetlands, may take longer than if there was active restoration and this might result in an increase in foregone services and thus an increase in associated damages. The relationship of these decreases for restoration costs and potential increases in damages for foregone services may require further evaluation in selected cases.

There is considerable controversy on all sides over the use of the contingent valuation methodology (CVM) particularly as it is applied to obtaining values and estimating damages for non-use services provided by natural resources. This controversy is likely to continue for some time and may finally be settled in the courts.

There are numerous other issues in the DOI proposed rules published in the April 29, 1991 Federal Register that may result in additional legal challenges and court rulings. For example, the DOI provides little guidance on the whole issue of restoration alternatives and is explicit that the most cost-effective alternative need not be selected. At some point, a PRP may be faced with a restoration alternative selected by the trustees that will be very expensive and not demonstrably cost-effective. The PRP may challenge the decision in court to determine if a cost-effective and reasonable cost principle should not be applied to the selection of restoration alternatives.

Once the NOAA rules are proposed or promulgated, there are likely to be legal challenges by trustees (especially from the states), environmental organizations and the commercial and industrial community. This was the case for the DOI rules and it is unlikely NOAA will be more successful at pleasing everyone, regardless of

NOAA's intensive efforts to solicit input and support during the development of the rules.

We speculate, or at least hope, that the trustees will focus on the NRDA process as a cooperative one that includes the trustees and PRPs, with the ultimate goal being restoration of the foregone services provided by natural resources. The process has not been cooperative; in fact, it has been generally litigation-oriented and thus decidedly non-cooperative. This approach does little to benefit the injured natural resources or to restore the foregone services.

We speculate expect that the NRDA process, in some form, will be established in other countries such as Canada, Australia, New Zealand, and possibly Mexico and parts of Europe. Any nation that decides to adopt an NRDA process for oil spills (or any other hazardous material release) should carefully investigate, analyze and evaluate the experience of the United States and make appropriate modifications.

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RISK ASSESSMENT INITIATIVES IN THE U.S. BEAUFORT SEA

by

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ABSTRACT

The Minerals Management Service (MMS) has recently acquired new data products and dynamic models for use in evaluating oil-spill risk in the Beaufort Sea. The improvement of risk assessment tools has taken three directions: improving meteorological data for the region, developing a stand-alone ice model, and developing a coupled ice-ocean model. This suite of models provides the flow fields that can be used to simulate hypothetical oil-spill trajectories. The MMS is developing suitable algorithms from the results of these models to deal with trajectory movement. These models, separately and in the coupled mode, are undergoing skill assessment and validation. The models will be used to create hypothetical trajectories that will be compared with the tracks of arctic drifting buoys.

INTRODUCTION

The Minerals Management Service has recently contracted for meteorological and ocean circulation models for use in evaluating oil-spill risk in the Beaufort Sea. The improvement of these risk assessment tools has been in three lines: improving meteorological data for the region, developing a stand-alone ice model, and developing a coupled ice-ocean model.

METEOROLOGICAL MODEL

The meteorological model is the 2-dimensional version of the Danard (1989) prognostic model for surface wind, surface temperature, and height of the atmospheric boundary layer (figure 1). The model considers the effects of topographic relief and atmospheric stability on the surface wind. The inputs to the model are the sea-level pressure, 1,000-millibar (mb) temperature, 850-mb height and the 850-mb temperature from the National Weather Service (NWS) National Meteorological Center meteorological model. Additional inputs are sea surface and ice concentration fields, which are updated monthly, with the possible future upgrade to daily updating for the coupled ice-ocean model. The lapse rate (temperature gradient) computed between 1,000 mb and 850 mb is used to calculate the temperature at the grid points. The pressures, heights, temperatures, and lapse

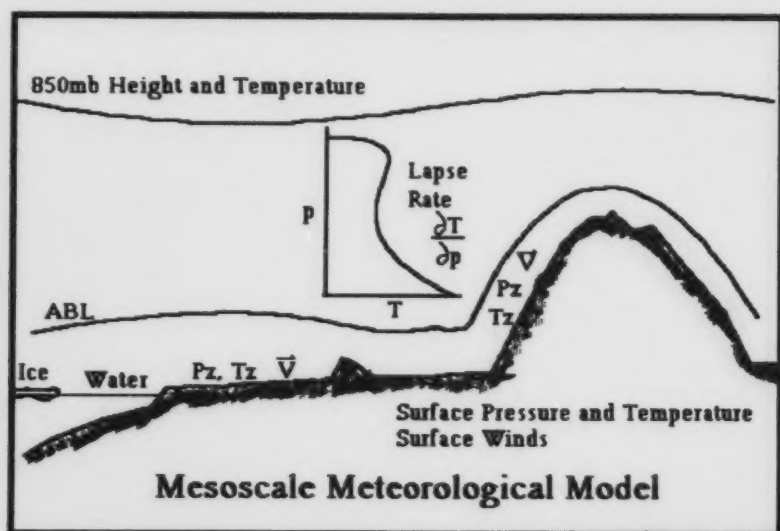


Figure 1 Schematic of the meteorological model.

rates are interpolated to the high resolution grid points (figure 2). The temperature at the terrain height is then calculated from the 850-mb temperature and the lapse rate. Then, the atmospheric boundary layer parameters (balanced wind, boundary layer height, heat flux, friction velocity, etc.) are estimated. The terrain height pressure is calculated from the terrain height temperature, sea-level pressure, and boundary layer parameters. The surface wind prognosis is then calculated from the surface pressure, balanced wind tendency, terrain slope gradients, and boundary layer friction terms. The final product is a modified windfield. At present, the model provides 10-km resolution over the Beaufort Sea. This resolution was applied over a grid of 256 by 271 points throughout calendar year 1983 and will be applied to other years as data are required.

The results of this model show the strong influence of the topography over the Brooks Range (figure 2). The steep slopes and high elevations of this range have been shown earlier to have a strong influence on the windfield (Kozo, 1980). Detailed analysis shows topographic steering around the peaks and flow through the passes. Wind speed comparisons were conducted using NWS stations at Barrow, Deadhorse, and elsewhere. The results of these comparisons indicate the improvements in the wind estimates. Times series of windspeed were also plotted, and these show that the modeled wind has maintained the time phase of the windspeed variations very well. The model is capable of data assimilation. However, due to data limitations, the present model runs did not use this option. The data were reserved for comparison with model output.

ICE MODEL

The ice model is a modified version of the Hibler and Bryan (1987) coupled ice model. The ice-alone model is a modified version of the Hibler (1979, 1980) code. In stand-alone mode, the model uses geostrophic (or other) currents and a parameterization of the heat fluxes. The model relies on a viscous-plastic rheology to represent the ice constitutive law. The ice mass is characterized by thickness and compactness. The conservation of ice equation includes thermodynamic sources and sinks. The ice responds to wind forcing through air-ice stresses and ice-water stresses (figure 3). The ice

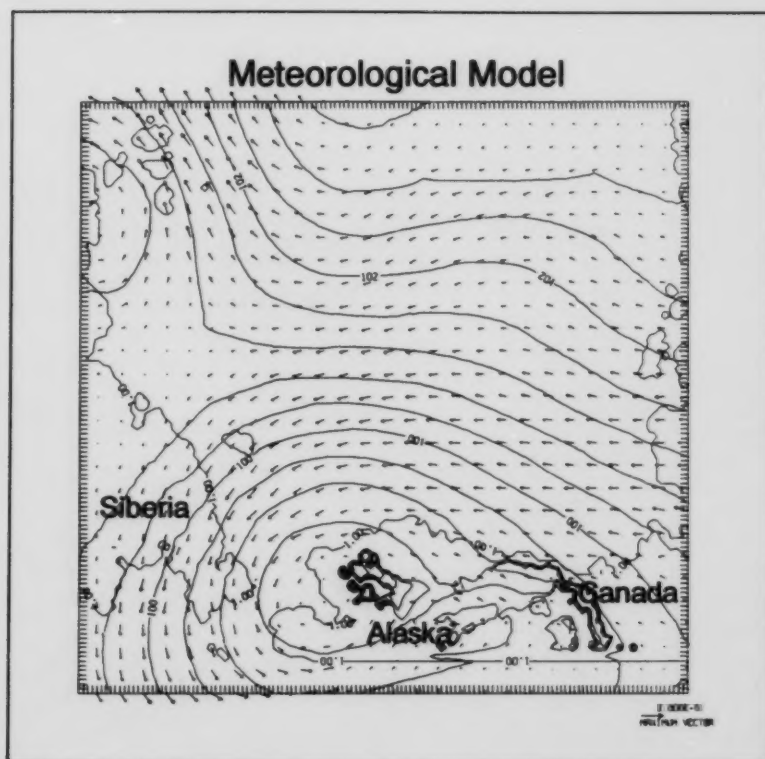


Figure 2 Wind and Surface Pressure output from the meteorological model.

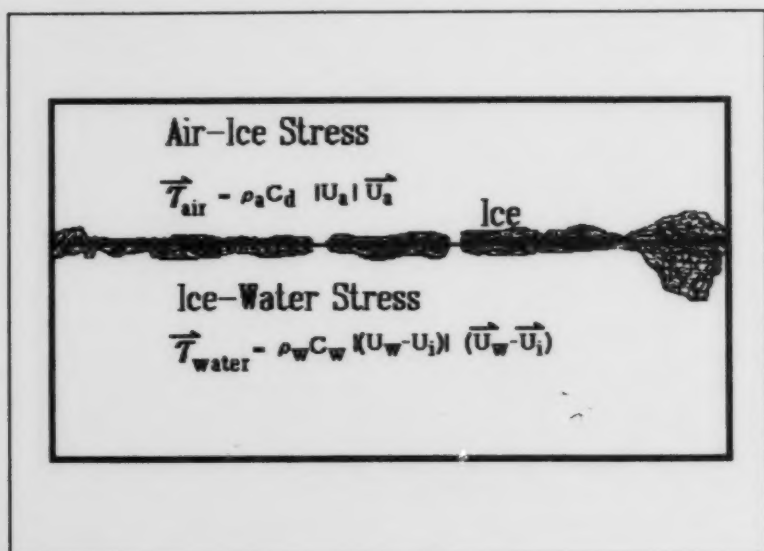


Figure 3 Schematic of the air-ice and ice-water stress formulations.

melting and freezing is calculated using daily 1983 wind and heat fluxes. Boundary conditions at the open boundary specify the ice thickness and compactness of the ice for inward-directed ice velocity as a constant value. The model output produces ice edge, ice velocity, and ice concentration fields at 10-km resolution (figure 4). Results of the ice-alone model indicate that the model simulations are sensitive to the quality of the ocean current fields, and that the coupled ice-ocean model should be implemented.

The results of the ice-alone model were compared with data fields from the U.S. Navy/National Oceanic and Atmospheric Administration Joint Ice Center (JIC) data fields (figure 5). The comparison indicates that the ocean circulation model would likely produce a significant improvement compared with the ice-alone model. The model was then modified to use data assimilation of JIC ice-edge data and, thus, ice concentration fields close to the observed results. In this case, another data set (or a reserved subset) would be required to verify the results. The assimilative model simulations are being examined to determine if the process of assimilating the JIC data retains the appropriate physics in producing the velocity fields.

OCEAN MODEL

The ocean model is the Semi-spectral Primitive Equation Model (SPEM) of Haidvogel (Haidvogel, Wilkin, and Young, 1991). The SPEM ocean model uses a Chebyshev polynomial representation of the stretched (σ) vertical coordinate (figure 6) and a curvilinear grid in the horizontal plane. The ocean model contains realistic basin geometry and stratification. The model was modified from previous versions to allow masking of land points in the grid to produce a highly conformal grid for the Beaufort Sea. The SPEM was implemented with eight co-location points in the vertical and 129 by 129 grid points in the horizontal plane (figure 7). The model was initialized with climatological temperature and salinity fields. Calculations were first performed as an ocean model alone, before coupling to the ice model. These simulations reproduced the major features of the Beaufort Sea gyre (figure 8).

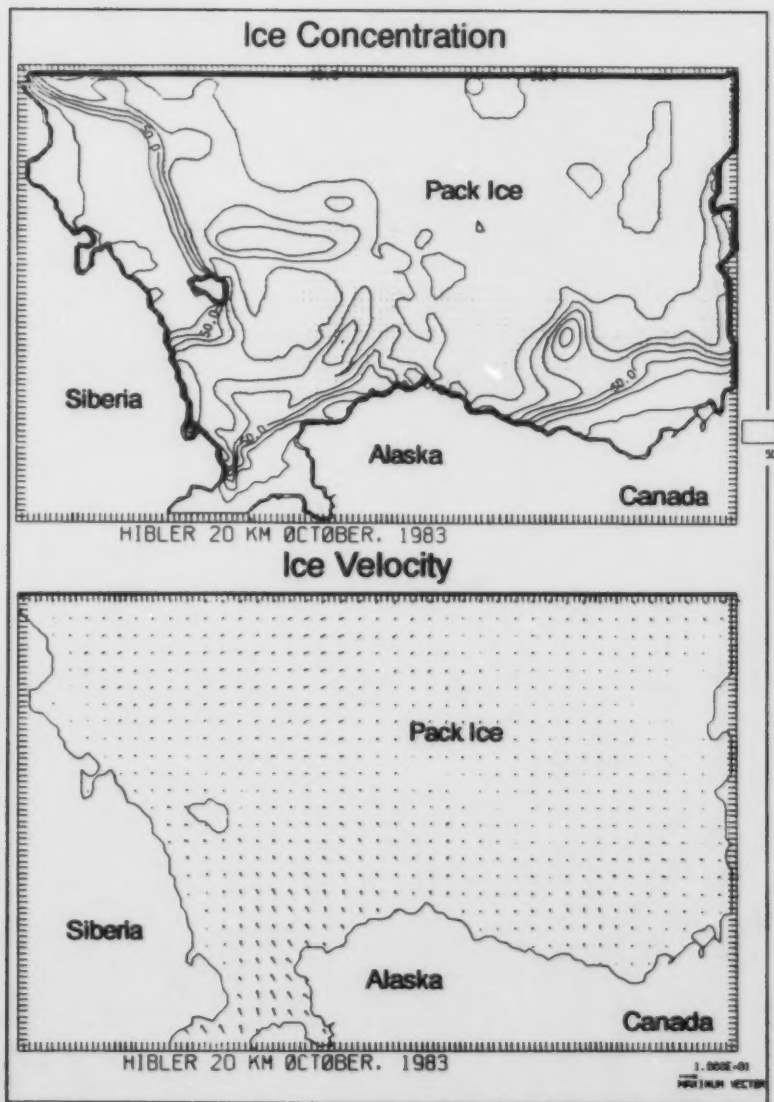


Figure 4 Ice concentration and velocity from the ice model.

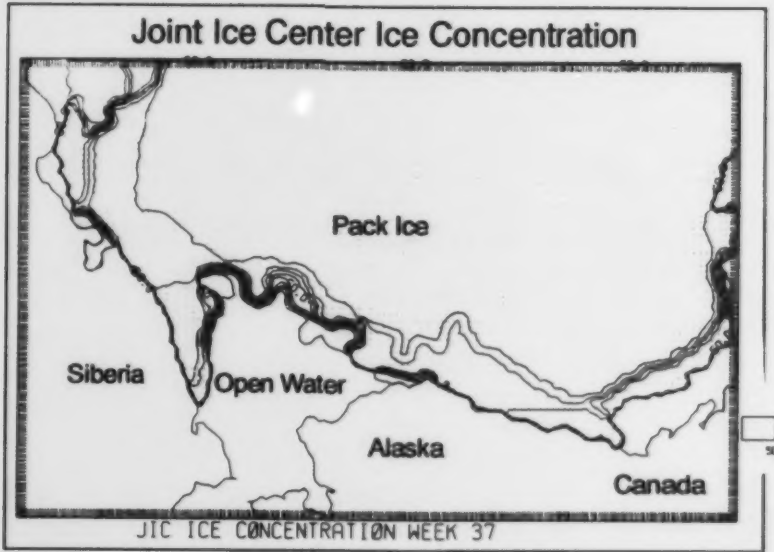


Figure 5 Joint Navy/NOAA Ice Center ice concentration map.

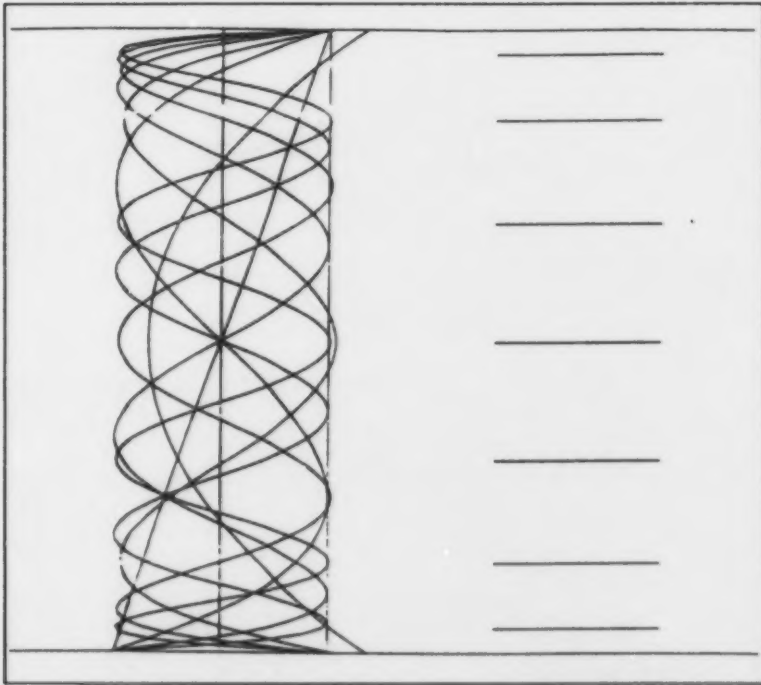


Figure 6 Schematic of the vertical coordinate of the SPEN ocean model. Shown are the modified Chebyshev polynomials on the left and the collocation levels for $N = 8$.

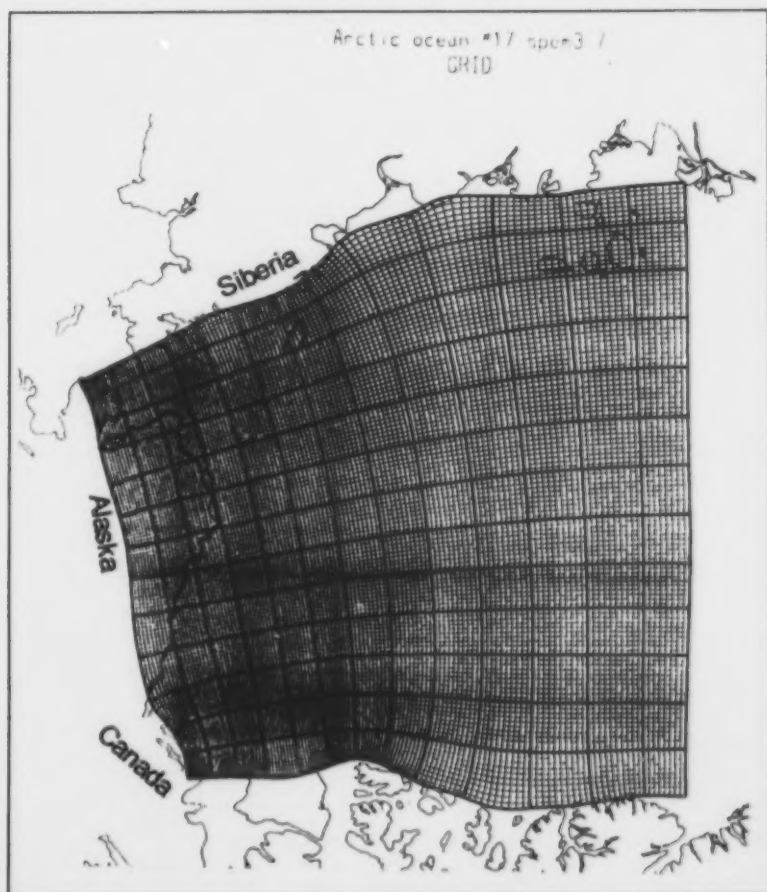


Figure 7 Chart of the SPEM grid.

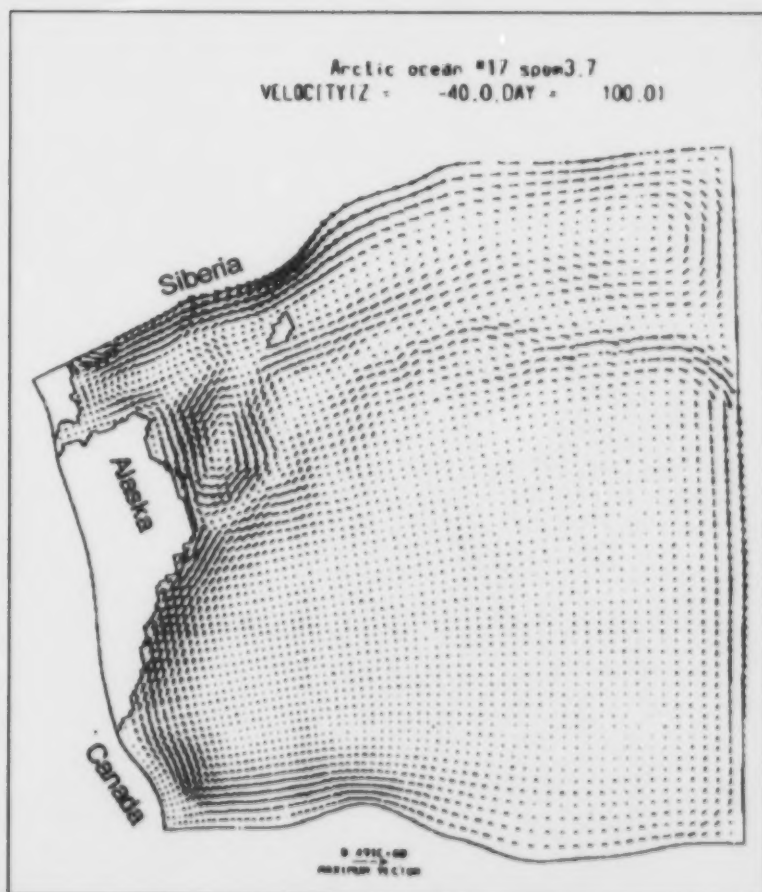


Figure 8 Velocity calculated by SPEN with wind forcing.

COUPLED ICE-OCEAN MODEL

The coupled ice-ocean model is the Hibler ice model coupled to SPEM. The models are coupled dynamically through the transfer of heat, momentum, and salt with the transfer mechanisms parameterized by the bulk formulae given in Riedlinger and Warn-Varnas (1990). The model was driven by daily winds and heat fluxes for 1983. The simulated ice-edge position and ice velocities compare well with available observations. Simulated trajectories of ice floes and water parcels also compare favorably to observed ice stations and drifters (figure 9). This suite of models provides the ice and ocean velocity fields that can be used to create simulated hypothetical oil-spill trajectories. Fleet Technology Limited is modifying and developing suitable algorithms to deal with trajectory movement through broken ice.

SUMMARY

The Minerals Management Service (MMS) has recently acquired new risk assessment products and dynamic models for the Beaufort Sea. These models, separately and in the coupled mode, are undergoing skill assessment and validation. If this analysis indicates significant skill within the model results, then they will be used to create hypothetical trajectories as part of the MMS oil-spill risk assessment process.

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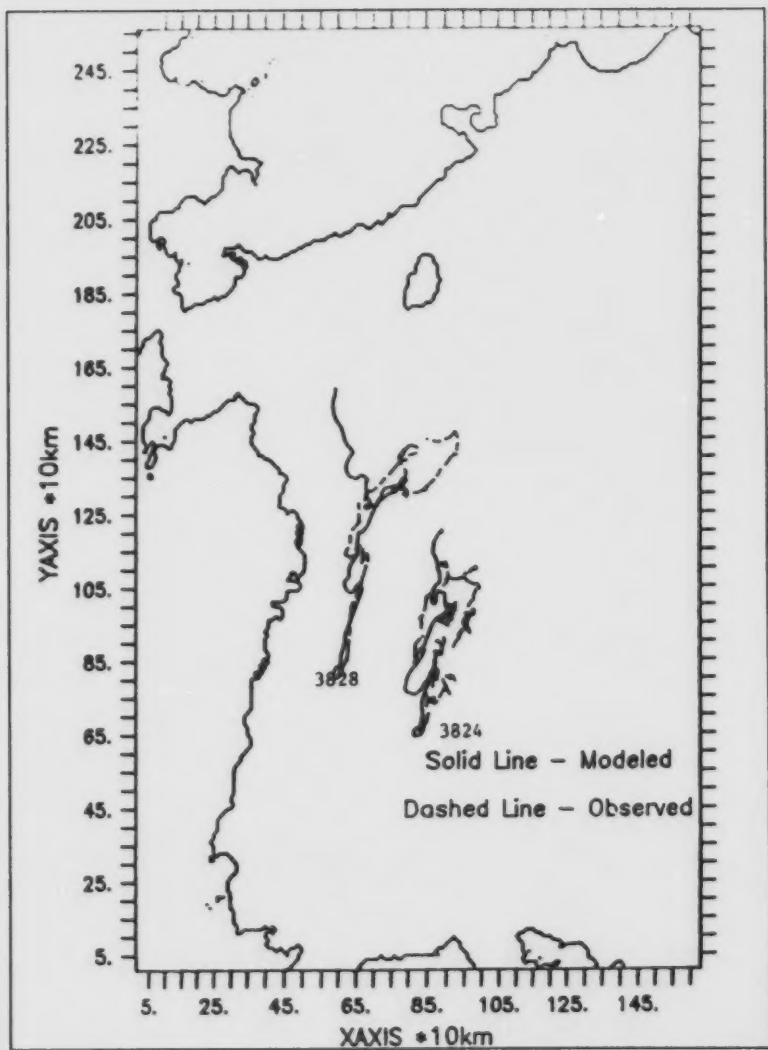


Figure 9 Observed ice station tracks and simulated trajectories from the model.

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PROBLEMS IN THE INTERPRETATION OF SPILL RESPONSE TECHNOLOGY STUDIES

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ABSTRACT

In view of the current renewed activity internationally of research in spill response technologies, it is increasingly important to recognize real and potential limitations to the interpretation of results of such studies. Past studies are often plagued by the use of inconsistent protocols and at times inadequate reporting of test methods. Also, intercalibration is only infrequently carried out, confounding comparisons among studies and making linkages between laboratory and field results difficult. Examples where these problems have arisen include the reporting of oil viscosity values, dispersant and demulsifier test methods, emulsion preparation methods, burning efficiency measurements, and data to support performance models. For future studies, there should be increased efforts in establishing test protocols which have wide acceptance. These should include requirements for increased rigor in the completeness of reporting test methods to allow better comparative interpretation.

INTRODUCTION

This paper deals with the major spill response techniques available today, the influence of weather and weathering processes on spilled oil, and the effectiveness and limitations of response techniques. This is done to indicate areas where interpretation of data may cause problems. Problems in interpretation of data may occur for the public, environmental agencies, response organizations, makers and users of response equipment and methods, as well as response planners.

BACKGROUND

There will always exist a potential risk for oil spills at sea that can cause environmental damage, associated with drilling and production activities and transportation of oil by tankers or pipelines. The high level of public concerns followed by the Exxon Valdez, Mega Borg and Haven oil spill incidents have resulted in a renewed international interest in research of spill response techniques. However, comparison of test results for various types of equipment and response methods are difficult because studies in the past often are plagued by use of inconsistent protocols, and at times the reporting of test methods and results are inadequate.

THE WEATHERING PROCESSES

When oil is spilled on sea, it is subject to several processes including spreading, drifting, evaporation, dissolution, photolysis, biodegradation, and formation of both oil in water and water in oil emulsions.

The weathering processes may lead to drastic changes in the chemical and physical properties of the oil and therefore also in oil behavior with time at sea. The main factors influencing the rate and extent of weathering are waves, wind, sunlight, air and sea temperature, and salinity.

Spreading, evaporation, and especially formation of water in oil emulsions, can cause a drastic increase in oil viscosity, and may therefore be of great importance for decision makers concerning the use of the different spill response techniques during an oil spill combat operation. It is therefore important that these parameters are assessed in relation to the time after an oil spill, and not only as some statistic oil property value.

SPILL RESPONSE TECHNIQUES

The choice of spill response techniques should vary depending on weather conditions, changes in the chemical and physical properties of the oil, and as a result of any delayed response time following an oil spill.

Major spill response techniques during an oil spill combat operation might include use of mechanical recovery equipment, in-situ burning, and chemicals or "soaps" as dispersants and demulsifiers. Figure 1 shows the relative efficiency of various response techniques.

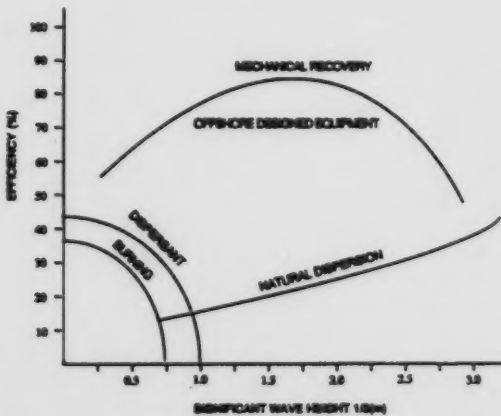


FIGURE 1: Effectiveness Of Response Techniques

Use of demulsifiers in order to prevent formation of or reduce emulsions on the sea surface, followed by use of dispersants, is a relatively new response method under development. Application of demulsifiers during mechanical clean up operations may also reduce the water content in the recovered emulsions and extend the time in operation in the field by decreasing storage requirements.

IN-SITU BURNING

Factors influencing ignition and combustion of oil floating on the sea surface are wind, waves, rain, initial oil thickness, oil thickness reduction, formation of emulsions, evaporation and dispersion (Allan 1991). However, the three main limiting factors for ignition and combustion of oil at sea are the oil thickness, oil thickness reduction, and the water content in the emulsion. A number of generalities of operational relevances can be made, drawn from both observational and experimental data.

Laboratory and mesoscale testing clearly indicate that ignition and combustion of oil having an oil thickness less than approximately 2mm is extremely difficult. The spreading of oil from a source on the open seas will within a short period of time cause a reduction of the thickness to less than 1 millimeter, making ignition and combustion impossible.

To allow ignition and in-situ burning at sea, use of fire resistant or fireproof booms are needed in order to create a sufficient oil thickness. Due to the heavy weight of fireproof booms, however, they have poor wave following characteristics and are reported to be ineffective in average waves higher than 3-4 feet. (3M Fire Containment Boom Specifications)

In wind velocities above approximately 2m/s or 4 knots the emulsification process takes place within minutes and may increase the water content up to 60-80% within a few hours. An effective limitation for ignition and combustion, however, is in the range of 30-50% (Allan 1991).

The efficiency of in-situ burning is claimed to be above 50% and often above 90%, depending on oil type and weathering properties. For emulsions, however, the efficiency has been as low as 10-35% (Etkin 1990). In either case, the methods used for efficiency calculations are not standardized and do not include emission of soot and smoke to the atmosphere or oil loss over or under the boom barrier. Taking into account soot and smoke, as well as boom losses, the actual level of oil burning efficiency can be expected to be below the maximal 90% mentioned. Better definition of this issue is needed.

In-situ burning may in the future be a common response technique. Responders will therefore need realistic data on the possibilities, limitations, and the effectiveness of in-situ burning for various fireproof booms, oil products, and weather conditions.

A simple equation for mass balance for oil burned would be:

Quantity of Oil Burned = Oil available for burning - Residue - Smoke and Soot - Loss of Oil from Boom System.

Quantitation of these elements is difficult under experimental conditions, and extremely so in real spill circumstances.

DISPERSANTS

Dispersants have been used for removal of oil spills from the sea surface since the Torrey Canyon incident 25 years ago, when they were used for the first time in a major oil spill. In the U.S., for instance, dispersants have been hampered due to perceptions of high toxicity and relatively low efficiency. The actual effectiveness of dispersants used at sea under the many different oil spill situations requires further understanding.

Most of the studies on effectiveness of dispersants used in the field indicate effectiveness values in the area of 20 to 70%, but most values are below 35% (NIST 1988, Allan 1991). However, it is very difficult to measure the effectiveness of dispersants used in the field and no common standard methods are available for establishing a mass balance. Laboratory effectiveness testing of dispersants may also give variable values since at least three different test methods are used (MNS, IFP, and WSL) (Daling and Brandvik 1990). The variations in experimental parameters like turbulence or energy input, settling time, and oil water ratio in various test apparatus are found to be important for the effectiveness values. The three test systems represent a low, medium, and high mixing energy methods, claimed to represent three different weather conditions or sea states, but today no real correlation exists between the mixing energy within the apparatus and the mixing energy in the ocean.

The effectiveness of dispersants will vary depending on many physical and chemical factors; such as: oil properties, application method, droplet size, oil thickness, dosage rate or dispersant to oil ratio, wind, and wave conditions, salinity, temperature, viscosity, pour point and emulsification.

MECHANICAL RECOVERY

Mechanical equipment based clean up continues to be the most common response method for oil spills. Among mechanical recovery equipment, there exists a large number of booms and skimming principles. The equipment tends to be designed for operation in calm, protected or open ocean areas, and skimmers are often designed to operate within certain viscosity ranges. Their performance capabilities and effectiveness will therefore depend on the area of operation and the weathering properties of the oil, in particular the sea state, oil type, oil thickness, and degree of emulsification.

For the purpose of testing and evaluation of mechanical clean up equipment, establishment of a viscosity code, ranging from approximately 100 to 1,000,000 cp should be developed. This will enable comparison of performance data for various clean up systems and principles, and makes it possible to choose the most effective equipment during a clean up operation. (Figure 2).

SKIMMER PERFORMANCE DATA

VISCOSITY (cst)	SKIMMER PRINCIPLES					
	A	B	C	D	E	F
100						---
			---	---		---
			---	---	---	---
	---			---	---	
	---	---	---		---	
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1,000,000						

FIGURE 2 : Skimmer Performance Data

A non-Newtonian liquid like a mixture of water and oil may have several apparent viscosities, depending on the measuring method, shear rate and temperature used in the analysis. It is critical for comparison of test results, and capacity and effectiveness data for various response techniques (especially for mechanical clean up equipment, pumps, and dispersants) that viscosity values are reported in a manner that avoids confusion and misinterpretation. Analysis parameters should always be provided.

PREPARATION OF EMULSIONS

Testing of oil spill response equipment as various skimmers and skimming principles and chemical treating agents as demulsifiers and dispersants by using emulsion may lead to different results as no standard protocols exist for preparation of emulsions for test purposes. Mixing of emulsions in laboratories for testing of dispersants and emulsifications, is often done by the rotating flask method by using fresh crude oils or oil products. In other test situations, the basis for mixing emulsions may be weathered or evaporated crude oil product with a specific boiling point as reference. The degree of weathering may vary from test to test, as well as the water droplet size, water content, viscosity, and temperature. Time standardization for preparation and subsequent analysis of a test emulsion is also critical for interpretation of results.

For mesoscale and full-scale offshore testing, bulk scale standard methods of mixing large quantities of emulsions are required. Mixtures of bunker and diesel oils, as well as topped crude oils, have been used to simulate degrees of weathering of spilled oils.

In conclusion, a standardized guideline for preparation and testing with emulsions is needed, allowing comparison of test results for chemical treatment agents and mechanical cleanup equipment.

NEW METHOD FOR TESTING OF WEATHERING PROPERTIES OF OILS

A new approach for characterizing the behavior of oil spilled on the sea surface has been developed by IKU, in the SINTEF Group, Norway (Daling and Brandvik, 1990). The approach includes an extensive mesoscale laboratory investigation of oil properties when exposed to weathering.

In the IKU method, the experimental data from the standardized laboratory investigations of the oils from both "step-wise" and mesoscale flume weathering tests are translated to field conditions by a numerical weathering model. The model predicts the rate of weathering processes of various oil types at sea under a range of weather conditions.

The method represents an important tool for contingency planning and for responders to facilitate decision-making on the use of different oil spill response techniques. Figure 3 shows a program printout of change in viscosity of water-in-oil emulsion.

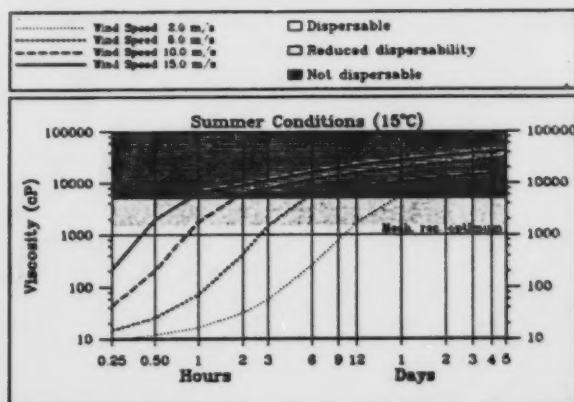


FIGURE 3: Change In Viscosity Of A Water-In-Oil Emulsion Related To Countermeasure Applicability.

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ASSESSMENT OF THE TRANSREC-350 MECHANICAL RECOVERY**CAPACITY OF THE OIL SPILL RESPONSE****EQUIPMENT IN PRINCE WILLIAM SOUND**

by

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PREFACE

When the Alaska Legislature in 1990 passed House Bill 567 into law the Alaska Department of Environmental Conservation (ADEC) realized that a procedure would have to be developed to determine what level of mechanical cleanup capability would fulfill the planning requirements of the new law as set forth by the planning standard in Alaska Statute 46.04.030 (k)(3)(C). Various empirical methods were evaluated in an effort to arrive at a defensible method for determining the mechanical recovery capacity needed to achieve the new planning standard in Prince William Sound to contain or control and clean up within 72 hours a discharge to open water of 300,000 barrels of oil. Since Alyeska was planning on utilizing **Framo TRANSREC 350 (TRANSREC)** skimmers we started gathering all available data on the performance of these skimmers. After reviewing the data, the work of the Norwegian's North Seas Operators Clean Seas Association (NOFO) appeared to present the best approach to develop a logical process for evaluation of the mechanical recovery capability of Alyeska's skimming systems.

For the purposes of this analysis the determination of compliance with Alaska's planning standard, is based on the quantity of oil recovered during the "worst" average weather conditions expected over a 72 hour period during which safe recovery operations could be conducted. It is assumed that a quantity of the 300,000 barrels of oil discharged is not available for recovery due to losses by evaporation. It is also assumed that the water fraction brought on board the barges, as the emulsion is recovered, is discharged (or decanted) into the boomed area. These are

two policy questions that have not yet been resolved within ADEC and which, depending on the decision, could impact the determination of compliance with the planning standard as presented in this paper.

ADEC has worked closely with the Prince William Sound Contingency Planning Steering Committee to develop a method for assessing the mechanical recovery capability of Alyeska's skimming equipment, especially the barge mounted **TRANSREC** systems. This group has attempted to agree upon concepts associated with contingency planning activities in Prince William Sound and to identify and use generally accepted data developed through actual oil on water skimming exercises or tests. The Steering Committee is made up of members from the State of Alaska, the U.S. Coast Guard, the Prince William Sound Regional Citizens Advisory Council, Alyeska and the Prince William Sound Tanker Association. This paper is the result of the attempt to reach a consensus on the method to quantify the capabilities of Alyeska's Ship Escort Response Vessel System (SERVS) equipment using the knowledge and experience of Steering Committee members.

A number of individuals have contributed to this report. Dan Lawn of ADEC did the statistical analysis of Prince William Sound weather data to provide a basis for taking the weather expected over an average 72 hour period into account and provided technical review. Larry Dietrick of ADEC provided valuable technical review and comments. Craig Rassiner of Exxon helped to edit and rework the report to make it technically accurate and to put it into a more readable format. Bob Levine of Arco provided a thorough technical review which helped to clarify many points. Tim Robertson, Tom Copland and Joe Banta of the Prince William Sound Regional Citizens Advisory Council provided needed critiquing and comments and helped to clarify various points. Nick Mitchell of Alyeska and Graham Lascelles an Alyeska contractor at the time of review provided technical review. Commander Ed Thompson of the U. S. Coast Guard also provided insight on various concepts and support. The mention of these individuals should not be construed that they are in agreement with the entire contents of this paper.

SUMMARY

In reviewing the data, the work of the Norwegians' North Sea Operators Clean Seas Association (NOFO) appeared to provide the best available data to meet the purposes of this paper. This paper is based upon the observed performance of the Framo **TRANSREC**, which represents a large portion of the initial response skimming capability of the SERVS equipment.

Based on the equipment and methodology and assuming volumes for evaporation and decanting described in this paper, the volume of oil expected to be recovered under the "worst" average weather conditions

would be 188,900 barrels. This volume of oil would be expected to expand as it gains water through the formation of an emulsion and assuming a 35/65 water to oil emulsion ratio, this volume would become 303,000 barrels. In addition a volume of "free" water taken in with the emulsion would also add to the volume of liquid that would have to be stored. The quantity of water, reduced by the process of decanting, would amount to 79,300 barrels. Overall, there would be 382,300 barrels of storage capacity needed. Thus, it is expected that to meet the standard, Alyeska's eight **TRANSREC** skimmers, mounted on four barges, would be required to recover and store 382,300 barrels of emulsion and un-decanted water. With the present configuration of skimmers and barges, the maximum available storage capacity is 370,000 barrels. Alyeska can maximize **TRANSREC** skimmers capabilities by matching storage capacity to recovery capability or by developing and demonstrating a capability to effectively off load the recovered oil from the barges in such a manner that transfer operations do not materially affect recovery operations.

While the skimming coverage that the four **SERVS TRANSREC** skimming units can provide has not yet been verified, it does appear that the present configuration of containment and deflection booms is sufficient for a 300,000 barrel discharge and to concentrate the slick giving the thickest possible oil layer and provides for maximum recovery capability and efficiency. Thus, the addition of more large high capacity **TRANSREC** skimming barges and the accompanying boom and boom tending vessels does not appear to increase skimming capabilities. There are a number of ways **SERVS** can continue to increase their proficiency and demonstrate their capabilities, however the most workable solution is to make daylight operations as efficient as possible by conducting frequent training exercises and occasional large scale drills. **SERVS** personnel have demonstrated increases in their level of proficiency in the use of the skimming capabilities provided in their inventory, particularly the **TRANSREC** units. It is anticipated that additional training will further enhance this proficiency. The goals should be to ensure that the response is carried out to make the most effective use of the existing equipment by increasing recovery efficiency through measures to reduce boom losses and achieve maximum oil thickness by incorporating technology applications to improve recovery operations during hours of darkness.

The following recommendations should be considered as a guide to Alyeska or any other spill response organization in working toward attaining improved operations:

- Continue training **SERVS** crews in the use of equipment;
- Send crews to participate in Norwegian oil on water recovery drills;

- Train crews in lightering operations from response barges, including rigging of and use of equipment;
 - Train with fishing vessel crews in boom deployment;
 - Train in the use of emulsion breakers, if its use is determined appropriate.
- Continue to develop plans for effective deployment and use of response resources under varying weather conditions;
 - Develop specific plans showing how other recovery equipment in the inventory will be integrated into the response plan;
 - Develop a strategy to increase the operational time of initial response equipment by determining means to off load recovery barges to get them back into service, or optimize the use of skimmers and storage capacity to make full use of the time available for skimming;
 - Investigate the use of emulsion breakers to increase storage capacity of barges;
 - Develop a means to accurately record Prince William Sound weather data to better estimate weather impacts on recovery efficiencies;
 - Assess the capability, use and development of secondary mechanical skimming equipment.
- Continue to carry out frequent response equipment deployment exercises to demonstrate capabilities of crews and equipment;
 - Demonstrate ability to respond to the scene of an incident and deploy equipment within specific time-frames;
 - Demonstrate ability to effectively operate and maintain the **TRANSREC** skimmers and supporting equipment for sustained periods of time, including back-up capability for equipment failures;
 - Demonstrate ability to increase effective operational time of equipment, by utilizing plan to lighter recovered emulsion in a timely manner;

- Demonstrate ability to utilize emulsion breaker, if a strategy is developed, to increase storage capacity.
- Continue to review new and developing technology, and technology applications to enhance existing capabilities;
 - Review applications of new technology for night-time skimming operations and incorporate new technology, and techniques as they become available;
 - Develop a better understanding of local current patterns and incorporate this knowledge into a plan for more effective nighttime recovery operations;
 - Review various boom systems and deployment strategies to determine what increases in overall emulsion recovery efficiency can be achieved.

BACKGROUND AND ASSUMPTIONS

This analysis of the skimming capacity of the SERVS equipment is directed primarily at the capability of the Framo **TRANSREC** skimmers which comprise a large portion of the SERVS skimming capability. This analysis is based on data obtained during the actual emulsified oil on water skimming biannual exercise conducted by the Norwegians' North Sea Operators Clean Seas Association (NOFO) over the past 4-5 years and is supplemented with information gained from experience during other drills and on water exercises (without oil) in Prince William Sound by the state, SERVS, the Coast Guard, and Exxon, B.P., Arco and Chevron over the past eighteen months. All of the work done by the Norwegians is based on the Framo **TRANSREC** skimmer. The level of equipment efficiencies and the degree of the Norwegian's proficiency with this equipment is based on the experience they have gained through these exercises. Therefore, the results of this analysis are based upon the level of performance expected from well-trained crews that have experience in operation of the skimmers and have been involved in actual oil skimming operations.

The following are the pertinent assumptions and summarized data presented by the Norwegians as taken from the "Operations Manual - Oil Spill Combat, Guidelines for Mechanical Recovery, January, 1989" and the Summary Reports for their Oil On Water Exercises for 1987, 1988 and 1989, as well as the data from the 1990 exercises. The 1990 data had yet to be published during the time frame of this report.

- Experience shows a skimmer emulsion recovery rate of 1,100 bbls/hr. can be achieved, which represents a skimmer efficiency of approximately 80% of the actual field pumping capacity;

- The amount of water that can be separated from the emulsion using an emulsion breaker is taken to be approximately 70 %;
- A system efficiency of 80% has been established due to the loss of emulsion either missing the booms or escaping under the booms reducing the amount of emulsion available for recovery;
- The small size of storage tanks on the recovery vessels, and incomplete separation of "free" water from the emulsion results in only about 60% of the water available for decanting back into the boomed area;
- The calculations for recovery and storage capacity are based on meeting a recovery requirement to control a spill of 8,800 m³/day (approximately 55,000 barrels/day) and that evaporation of approximately 50% for spilled crude oil produced from the Norwegian North Sea Basin will occur;
- The use of large deflection booms and fewer recovery systems to reduce boom losses and increase recovery efficiency is preferred;
- Multiple skimming groups are used in formation with back-up systems;
- Recovery units should be positioned at a suitable distance from the source, so that weathering processes assist in emulsion stiffness;
- "De-rating" of the skimmers for night or poor visibility operation is not considered since the Norwegians believe they can calculate the main currents for purposes of positioning equipment. (Since all their oil platforms are at fixed locations, and they have good knowledge of local currents, it is reasonable to expect that positioning of recovery equipment could be accomplished with some degree of success. The Norwegians have also had some success with forward looking infrared [FLIR]. During the 1990 exercise, the Norwegians claim to have recovered 62% of the oil spilled during a nighttime portion of the exercise).

In addition to the above factors derived from the Norwegian's experience that have application in Prince William Sound, various factors appropriate for Alaska North Slope Crude have been included and local weather data has been incorporated into the analysis as has other specific pertinent information as follows:

- Alaska North Slope Crude oil has an apparent evaporation of 18% of oil spilled;
- Response time is assumed to be about six hours for all four major response units. This time accounts for transit as well as making the equipment ready for skimming.
- A four hour maintenance period has been included for each of days two and three, resulting in a total of 58 hours for actual skimming operations during the 72 hour period;
- Skimming capabilities are calculated for eight **TRANSREC** skimming units distributed equally among four skimming platforms. The skimming platforms are assumed to have storage capacities of 73,800, 77,000, 135,063 and 148,238 barrels respectively;
- The recovery values used in this analysis are based on the performance of the **TRANSREC** skimmers used in the Norwegian exercises. It is assumed that the boom and configuration utilized by Alyeska will be as effective as the ocean boom and configuration utilized by the Norwegians in the North Sea;
- The influence of weather is based on an analysis of weather data collected by the **SERVS** vessels (Table 1) during the winter of 1990 and 1991. This analysis (Table 2) provides average sea states which might be expected to occur during any average period of time;
- Alyeska and the fishing vessels have demonstrated that the **TRANSREC** skimming units and boom can be deployed and formations made-up and maintained at night. It also is apparent that by using spotter vessels and barges equipped with crab lights, effective skimming operations could be carried out at night during the early hours of a spill.

OPERATIONAL CONDITIONS

There are certain pertinent and underscoring factors which have significant impacts on the fate of a large oil spill, and on the efficiency of the equipment responding to the spill. An attempt to quantify these factors for Alaska North Slope Crude and Prince William Sound is included in this paper.

Wind/Sea Height. During the winter of 1990/1991, **SERVS** vessels collected data on wind speeds observed during the transits of Prince William Sound. The following Table highlights the results of that data.

TABLE 1 ¹			
WIND SPEED, DURATION AND EXPECTED SEA HEIGHT			
WIND VELOCITY (KNOTS)	DURATION OF WIND (HRS/72 HRS)	PERCENTAGE OF TIME	EXPECTED SEA HEIGHT ² (METERS)
UP TO 10	18	25	UP TO 0.9
11 TO 20	28	39	1 TO 2
21 TO 30	17	24	2.1 TO 2.7
31 & OVER	9	12	2.8 & OVER

Utilizing this data, and applying the resulting expected sea height factors developed by NOFO in their Operations Manual, an expected skimmer efficiency, expressed as a percentage of the pumping capacity (which takes into account head, cavitation, debris, etc.) can be determined. The NOFO data shows an actual emulsion recovery rate, or skimmer efficiency, which represents 80% of the actual field pumping capacity in seas up to one meter. Other skimmer efficiencies for other sea heights were determined from the NOFO data as shown in the following table:

TABLE 2	
SEA HEIGHT AND SKIMMER EFFICIENCY	
SEA HEIGHT (METERS)	SKIMMER EFFICIENCY ³
UP TO 0.9	80%
1 TO 2	70%
2.1 TO 2.7	50%
2.8 & OVER	10%

¹ Lawn, Daniel, 1991. Prince William Sound Wind Speed Analyses: For Tanker Operating Conditions, ADEC document.

² From Beaufort Scale. It is recognized that the Beaufort Scale is based on open ocean, long period waves whereas storms in Prince William Sound tend to generate short period waves. This could result in lower skimmer/system efficiencies especially in winds from 20 knots and higher. The dampening effects of the oil on the waves and skimming in the lee of the barges will have a positive impact on the skimmer/system efficiency.

³ The noted efficiency is a low average from the NOFO Manual graph.

Evaporation/Emulsification/Escapement

The literature shows for Alaska North Slope Crude, during the initial response period of 72 hrs, the amount of the total volume of oil spilled that will either evaporate or disperse/dissolve into the water column ranges from 15-18% during the first 24 hours, to 17-20% after 48 hours and reaches 18-22% after 72 hours.^{4,5} An average over the three day period is 18% which is used in the calculations.

It is also assumed that, for varying reasons of system inefficiencies, an additional 20% of the remaining volume will escape effective, initial containment. This value is taken from the experience of the Norwegians during their oil on water exercises.⁶

An average degree of emulsification for North Slope Crude over the initial 72 hours from the incident was determined from the data of Payne and McNabb to be 27%.⁷ From this data the state assumed that over a 58 hour skimming period encountering an average 35/65 water to oil emulsion would not be unreasonable when considering the "worst" average weather conditions.

Based upon these two assumptions, the following equation is derived utilizing these factors:

⁴ Schulze, Robert and Lissauer, Ivan, 1985. An Overview of a Field Guide for Arctic Oil Spill Behavior. *Proceedings of the 1985 Oil Spill Conference*. American Petroleum Institute, Washington, D.C., pp399-403.

⁵ Payne, J.R., and McNabb, Jr., G.D., 1984. Weathering of Petroleum in the Marine Environment. *MTS Journal*, V18, N3, pp24-42.

⁶ This oil which escapes is assumed to be addressed by other response equipment within the Alyeska stockpile and the response capability is not estimated in this paper. The contained volumes of oil are addressed by the TRANSREC units only.

⁷ Payne, et al. Multivariate Analysis of Petroleum Hydrocarbon Weathering in the Subarctic Marine Environment. *Proceedings of the 1983 Oil Spill Conference*. American Petroleum Institute, Washington, D.C., pp423-434.

$$V_{re} = V_i \times K_1 \times E_{fac}$$

where

V_{re} = Volume of recoverable emulsion

V_i = Initial volume spilled

K_1 = 0.656 (82% remaining after evaporation and 80% of that remaining after escapement)

E_{fac} = Emulsification constant = 1/fraction of oil in emulsion

[Example: For an emulsion with an estimated water to oil ratio of 30/70, the emulsification factor would be 1/0.70 or 1.43.]

Thus, for an initial volume of oil spilled of 300,000 barrels with a water/oil ratio of 30/70, the resulting volume available for mechanical recovery would be approximately 281,000 barrels. This can be readily seen in the following calculation using the above formula:

$$281,000^a = 300,000 \times 0.656 \times 1.43$$

Utilization of this formula for other water in oil emulsion ratios gives the results tabulated in Table 3:

TABLE 3		
INCREASE IN OIL VOLUME DUE TO WATER UPTAKE (EMULSIFICATION)		
WATER/OIL RATIO	EXPANSION FACTOR	APPROXIMATE BBLs. EMULSION
30/70	1.43	281,000
35/65	1.54	303,000
40/60	1.67	328,000
50/50	2.00	393,000
60/40	2.50	492,000
70/30	3.33	656,000

Decanting/Free Water Pickup

^a Calculations of crude oil, emulsion and water uptake volumes are rounded off to the nearest 100 barrels.

Finally, a certain volume of "free" water will be pumped with the recovered emulsion. At this time, there are no plans to use emulsion breakers during response operations in Prince William Sound for separating water that actually combines with the spilled oil to form a stable emulsion. However, the so called "free" water will be in a separate phase from the emulsion and can be removed by the process of decanting. Considering the sizes of the SERVS barges, a high degree of decanting efficiency should be achieved. Successful decanting is, however, affected by sea height, settling time and decanting rate. It is assumed that decanting in various sea heights can be accomplished to different degrees depending on the amount of mixing occurring at the oil water interface. The varying degrees of decanting (the amounts of "free" water that can be pumped back into the containment boom as compared with the balance which is the amount kept on board) are shown in Table 4.

TABLE 4	
EFFECTS OF SEA HEIGHT ON DECANTING	
SEA HEIGHT (METERS)	DECANTING FACTOR
UP TO 0.9	0.8
1 TO 2	0.8
2.1 TO 2.7	0.7
2.8 & OVER	0.6

Calculation of Loading Rates

In order to develop a net loading rate for the recovery of emulsion the assumption used by the Norwegians was also used in this paper and the TRANSREC "total" pumping capacity was taken as a constant, regardless of weather conditions. To maintain this constant pumping rate, the TRANSREC operators must lower the skimming head deeper in the water in higher sea states. Obviously, the emulsion recovery rates will decrease according to deteriorating weather conditions, however total pumping capacity (and thus, the capacity of the unit) will remain the same.

The "loading" rate calculations utilized in this examination were made from the NOFO data accumulated in a number of oil on water exercises. This data shows that a single TRANSREC unit can consistently achieve an actual emulsion recovery rate of 175 m³/hour, or about 1,100 bbls./hour. Applying these figures to the SERVS skimming groups provides each skimming unit (2 TRANSREC skimmers each) with an emulsion recovery rate of 2,200 bbls./hour.

Utilizing the measured emulsion recovery skimming efficiency (80%) and the actual emulsion field pumping capacity (2,200 bbls./hour) from the NOFO data, the "total" pumping capacity of each SERVS unit can be calculated:

$$2,200/0.8 = 2,750 \text{ bbls./hour} = \text{"total" pumping capacity.}$$

Having established a "total" pumping capacity for each of the SERVS skimming units, and again assuming that the units will on the average recover this volume, the volume of emulsion recovered and the volume of "free" water pumped with the recovered emulsion can be calculated. This is accomplished by considering the "total" pumping capacity, the skimmer efficiencies at various sea states (see Table 1) which determines the emulsion recovery rates. The difference between "total" pumping capacity and the emulsion recovery rate is assumed to be the volume of "free" water recovered during skimming operations under varying sea heights. These are shown in Table 5.

TABLE 5			
EMULSION RECOVERY AND "FREE" WATER UPTAKE*			
SKIMMER EFFICIENCY (TABLE 1)	"TOTAL" PUMPING CAPACITY (BBLs./HR)	EMULSION RECOVERY RATE (BBLs./HR)	"FREE" WATER UPTAKE RATE (BBLs./HR)
80%	2,750	2,200	550
70%	2,750	1,925	825
50%	2,750	1,375	1,375
10%	2,750	275	2,475
* For a single skimming barge equipped with two TRANSREC skimmers.			

Now, using the decanting factor, as shown in Table 4, the emulsion recovery rate and the "free" water uptake calculations shown above, a "net" loading rate for each of the skimming units can be calculated. The "net" loading rate (the actual volumetric loading rate of the skimming units) is the sum of the Emulsion Recovery Rate and the "Free" Water Uptake Rate, less the volume of recovered "free" water which is decanted. This is shown in the following formula:

$$A = B + W - [W(d)]$$

where:

- A = "Net" loading rate
- B = Emulsion Recovery Rate
- W = "Free" Water
- d = Decanting Factor

Application of this formula to the data from Table 4 now allows the calculation of the "net" loading rate of each skimming unit under varying weather or sea height conditions.

TABLE 6				
NET LOADING RATES FOR VARIOUS SKIMMER EFFICIENCIES*				
SKIMMER EFFICIENCY (TABLE 1)	EMULSION RECOVERY RATE (BBLS/HR)	"FREE" WATER COLLECTED (BBLS/HR)	DECANTING FACTOR	NET LOADING RATE (BBLS/HR)
80%	2,200	550	0.8	2,310
70%	1,925	825	0.8	2,090
50%	1,375	1,375	0.7	1,790
10%	275	2,475	0.6	1,265
* For a single skimming barge equipped with two TRANSREC skimmers.				

At this point, it is important to highlight that these values are derived from data available, which is considered to be as accurate as possible. To this data, various factors have been developed and applied which can influence skimmer performance. The end results are seen as reasonable based on the assumptions made, although individual components of the formula may vary to a significant degree. While recovery performance is difficult to predict and it is very likely there may be noticeable variance from these calculated rates during an actual response, this approach provides a reasonable method to determine compliance with the planning standard.

RESULTS

Utilizing the data developed from the foregoing tables, the expected performance of the four TRANSREC equipped SERVS skimming units in responding to a spill of 300,000 barrels was assessed.

The following tables show the volume of emulsion which could be recovered by each skimming unit plus the quantity of un-decanted water remaining in the barges, at various loading rates. Of course, the quantity of oil recovered will depend on the water to oil ratio of the emulsion. These analyses correspond to potentially average weather conditions during any 72 hour period throughout the year. The first tabulation represents a "best" average weather and operating conditions and the second table represents the "worst" average weather conditions that an initial response group could find at the scene of an incident during which safe recovery operations could be sustained. "Best" and "worst" case conditions are developed depending on which weather condition is assumed as the starting point of operations.

The tables provide operational times in parenthesis, and the volume loaded at a particular "net" loading rate until each barge is filled to the capacity shown. The "net" loading rate includes recovered emulsion and the "free" water which was not decanted. The maximum operating time is 58 hours. It should be noted that the smaller barges reach their load capacities prior to 58 hours of operation.

TABLE 7 ^a				
TOTAL EMULSION AND "FREE" WATER UPTAKE [*]				
"Best" Average Weather Conditions				
"NET" LOADING RATE (BBL/S/HR)	BARGE MLC344 (73,800)	BARGE UT 10 (77,000)	BARGE 450-8 (148,200)	BARGE Z-BIG-1 (135,100)
2,310	(18) 41,580	(18) 41,580	(18) 41,580	(18) 41,580
2,090	(16) 32,220	(17) 35,420	(28) 58,520	(28) 58,520
1,790	---	---	(12) 21,480	(12) 21,480
1,265	---	---	---	---
TOTALS:	(33) 73,800	(35) 77,000	(58) 121,520	(58) 121,520
Total Recovered Emulsion plus Un-Decanted Water Volume = 394,000 bbls.				
"Worst" Average Weather Conditions				
1,265	(9) 11,385	(9) 11,385	(9) 11,385	(9) 11,385
1,790	(17) 30,430	(17) 30,430	(17) 30,430	(17) 30,430
2,090	(15) 31,985	(15) 31,985	(28) 58,520	(28) 58,520
2,310	---	---	(4) 9,240	(4) 9,240
TOTALS:	(41) 73,800	(43) 77,000	(58) 109,575	(58) 109,575
Total Recovered Emulsion plus Un-Decanted Water Volume = 370,000 bbls.				
^a Four skimming barges each equipped with two TRANSREC skimmers.				

PROJECTED OIL RECOVERY

The quantity of oil available for recovery by the TRANSREC units, utilizing the assumptions and data as presented in this paper, is established at approximately 196,800 barrels after considering evaporation, natural dispersion/dissolution and an assumed escapement.

In order to determine the quantity of oil recovered, the decanting factor from Table 4 is used along with the "free" water collection rates from Table 5 and the hours of operation and the total liquid retained on board the barges from Tables 7 and 8. This is accomplished through the use of the following formula:

^a Basic P.W.S. assumptions limit total operational time to 58 hours.

$$V_o = (T_{rec} - W_{fr}) \times E_{fac}$$

where:

V_o = Volume of oil recovered

T_{rec} = Total volume recovered

W_{fr} = "Free" water retained on board after decanting

E_{fac} = Water in oil emulsification factor

Computation of the volume of oil collected can be determined by using the information in the following table. The remaining "free" water collected on the barges is determined using the transposed decanting factor (1.0 - Decanting factor) which is multiplied by the volume of "free" water collected. The remaining "free" water is then multiplied by the number of hours of operation in Tables 7 to generate the "free" water retained on board after decanting.

TABLE 8			
RATE OF ACCUMULATION OF UN-DECANTED "FREE" WATER*			
NET LOADING RATE (BBL S/Hr)	"FREE" WATER COLLECTION RATE (BBL S/Hr)	TRANSPPOSED DECANTING FACTOR	REMAINING "FREE" WATER (BBL S/Hr)
2,310	550	0.2	110
2,090	825	0.2	165
1,790	1,375	0.3	415
1,275	2,475	0.4	990
* For a single skimming barge equipped with two TRANSREC skimmers.			

Thus, for a total volume of recovered product of 394,000 barrels as shown in Table 7 for the "best" average weather conditions, the resulting volume of oil recovered would be approximately 253,000 barrels. This can be seen in the following:

$$V_o = (T_{rec} - W_{fr}) \times E_{fac}$$

$$\begin{aligned} \text{where } W_{fr} &= (110)(72) + (165)(89) + (415)(24) \\ &= 32,600 \text{ bbls} \end{aligned}$$

$$253,000 = (394,000 - 32,600) \times 0.7$$

Using the quantity of liquid recovered (emulsion and un-decanted water) and remaining on board the barges as calculated in Table 7 for the "worst" average weather conditions, the resulting volume of oil recovered would be from approximately 174,000 to 203,500 barrels depending on the emulsification assumed as shown below:

For a 30/70 water to oil emulsion:

$$203,500 = (370,000 - 79,260) \times 0.7$$

For a 35/65 water to oil emulsion:

$$188,900 = (370,000 - 79,260) \times 0.65$$

For a 40/60 water to oil emulsion:

$$174,000 = (370,000 - 79,260) \times 0.6$$

Utilizing the data shown in Table 2, the volume of emulsion to be recovered can potentially increase from approximately 281,000 to as much as 656,000 barrels, depending on the amount of emulsification which occurs. Within the prescribed time frame, it is not likely that the oil will emulsify to the higher levels shown in that table for the "best" average weather conditions. We should expect to see a higher level of emulsification under the "worst" average weather conditions. Thus, if Alyeska arrives at the scene of a spill incident under the "worst" average weather conditions, with the higher sea states early during the response effort, the average emulsion encountered over 58 hours would likely contain greater than 30% water.

Taking the data from Tables 6 and 7 the decanting rates needed on the barges to pump the decantable portion of the "free" water can be determined. The "worst" average weather conditions are used and the available time for decanting is taken as 36 hours. The results are summarized in Table 9.

TABLE 9		
BARGE DECANTING RATES		
BARGE	WATER VOLUME DECANTED (BBLS)	DECANTING RATE (BBLS/HR)
MCL-344	39,600	1,100
UT-10	40,100	1,110
450-8	50,000	1,390
Z-BIG-1	50,000	1,390

These pumping rates should be readily achieved provided all the necessary components such as hoses, properly sized fittings, etc. are in place.

CONCLUSIONS

Under the "worst" average weather conditions, when the potential for higher water to oil emulsions will occur, the recovered oil calculations indicate that with the present configuration of barges, Alyeska would be unable to achieve the planning standard when the water to oil emulsion ratio is 35/65 or greater. Reviewing the data presented in the above Tables demonstrates that, for a spill where a 35/65 water to oil emulsion can be expected to occur, Alyeska would be required to recover with the **TRANSREC** equipped skimming units approximately 303,000 barrels of the emulsion (containing approximately 196,800 barrels of oil) in 72 hours. (From Table 3) Under these conditions Alyeska would be required to recover and store at least 303,000 barrels of emulsion and 79,300 barrels of un-decanted water or a total volume of 382,300 barrels. As the calculations from Table 7 show, Alyeska would only have the capability to recover and store 370,000 barrels which would yield 189,000 barrels of oil which is 7,900 barrels short of that expected to be recovered by the **TRANSREC** skimmers. Also, in weather conditions more severe than those used in the analysis, emulsion volumes might represent such a significant increase as to make attainment of the planning standard without additional resources unlikely.

It is evident that Alyeska has not planned for optimal use of the **TRANSREC** recovery capacity on the two smaller barges which are filled to capacity in 33 and 35 hours respectively, and has not planned for optimal use of storage capacity on the two larger barges which are not filled to capacity within 58 hours. The **SERVS** units are able to operate for a total of 184 hours under the "best" average weather conditions and for 200 hours under the "worst" conditions out of a total of 232 hours (four skimming barges each operating 58 hours). If Alyeska were to optimize use of the **TRANSREC** skimmers currently on the smaller barges so they could operate for the entire 58 hour period they could achieve an additional 93,000 and 43,800 barrels of recovery capacity under the "best" and "worst" situations respectively. Alyeska could also increase their capacity by adding additional skimming capacity on the larger barges and gain 40,000 and 64,200 barrels under the "best" and "worst" situations respectively. This additional capacity would certainly add some "safety factor" capability to deal with unforeseen problems such as equipment downtime, deployment delays etc.

Thus, it is evident that Alyeska must evaluate various options to make more efficient use of existing equipment and will have to implement measures to make maximum use of the **TRANSREC** systems under the "worst" average weather conditions to meet the planning standard.

At this point it may be useful to develop some generalized information concerning recovery rates to relate the recovery efficiencies for **TRANSREC** skimmers developed in this paper to the manufactures "nameplate" value. Thus, if each **TRANSREC** operates for 58 hours, the total quantity of oil and un-decanted water recovered for the "worst" average weather conditions (for a combined 232 hours of total operation) is 438,300 barrels. (This assumes **SERVS** has adequate storage capacity to allow this volume to be stored.) The un-decanted water portion amounts to 84,100 barrels of that quantity leaving 354,200 barrels of emulsion. The quantity of oil would be 230,200 barrels as calculated for a 35/65 water to oil emulsion. Utilizing the **TRANSREC** manufactures "nameplate" rating of 2200 bbls/hr, then eight of the units theoretically would recover 1,020,800 barrels of pure oil over the same combined 232 hours of operations. This translates to a recovery capability based on "nameplate" of 22.6% as calculated below. This percentage of "nameplate" can now be taken as the basis for calculating **TRANSREC** skimmer capacity.

TRANSREC Skimmer recovery rate as a percentage of the manufacture's rated "nameplate" equals

$$230,200 / 1,020,800 \times 100 = 22.6\%$$

This paper has limited its assessment predominantly to the **TRANSREC** equipped units, which represents a large portion of the skimming capability and recovery capacity of the **SERVS** equipment. In order to achieve the planning standard an additional 75,300 barrels of emulsion (containing approximately 49,200 barrels of oil) will have to be recovered with other equipment within the 72 hour period. However, other equipment such as the **VALDEZ STAR**, **SEA SKIMMERS** and **DOSEC ARMS** is available from the Alyeska stockpile and effective use of this additional equipment could provide additional versatility and compensate for any shortcomings which might appear from consideration of the **TRANSREC** equipped units only. Alyeska's **SERVS** has tentatively demonstrated in drills that the **VALDEZ STAR**, and the **DOSEC ARMS** as well as a near shore response effort could be used in conjunction with the other initial recovery groups as part of the strategy in meeting that portion of the planning standard (49,200 barrels of oil) that the **TRANSREC** skimmers will not recover. However, until the planning is accomplished and an implementation strategy developed to effectively deal with all aspects of this response effort, this capability will not be considered to be in place.

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RESPONSE AND MANAGEMENT STRATEGIES UTILIZED DURING THE KENAI PIPELINE CRUDE OIL SPILL, NIKISKI, ALASKA

by

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PREFACE

The grounding of the tanker vessel Exxon Valdez in March of 1989 and the release of oil into Prince William Sound precipitated an in depth evaluation of spill preparedness and response in Alaska. The State Legislature established the Alaska Oil Spill Commission which identified the need for increased vigilance in oil spill prevention, planning, and response capability for all areas of Alaska¹. Since 1989, many changes have been implemented in the State of Alaska to correct these problems. The oil industries and the State and Federal governments have made unique cooperative efforts to ensure that Alaska's environment is better protected. Although the prevention of spills is stressed as the best practice, there is recognition that spills will occur and that resources must be readily available to contain or control and clean up the oil.

An oil spill occurred from the Kenai Pipeline Company (KPL) during the early morning of January 4, 1992. The facility, located in Nikiski, Alaska on the east shore of Cook Inlet, consists of a refinery, several large above-ground storage tanks, and a marine terminal. The marine terminal facilitates the off loading of crude oil and ballast water from vessels and the loading of refined oil products to vessels. To de-ballast from the vessels to the facility, a 10-inch diameter steel line is utilized. The line is insulated and heated with an electric trace. Sometime before the spill, the heat trace system failed and the residual ballast water in the line froze causing a rupture in the line and the reported release of 1006 barrels of a water/crude oil mixture into Cook Inlet. The reported oil content of this release was between 100 and 400 barrels.

Cook Inlet is a large body of water approximately 25 miles wide and 150 miles long. It has the second largest tidal fluctuations in the world, frequently exceeding twenty feet, with tidal current velocities as fast as 8 knots. During the winter, ice is present in Cook Inlet with up to 100 percent coverage in some areas. Wind direction and velocity determine the sea states which can exceed three meters in ice free areas. Cook Inlet also contains areas of severe tidal convergence, locally called rip-tides, which tend to concentrate oil, debris, and

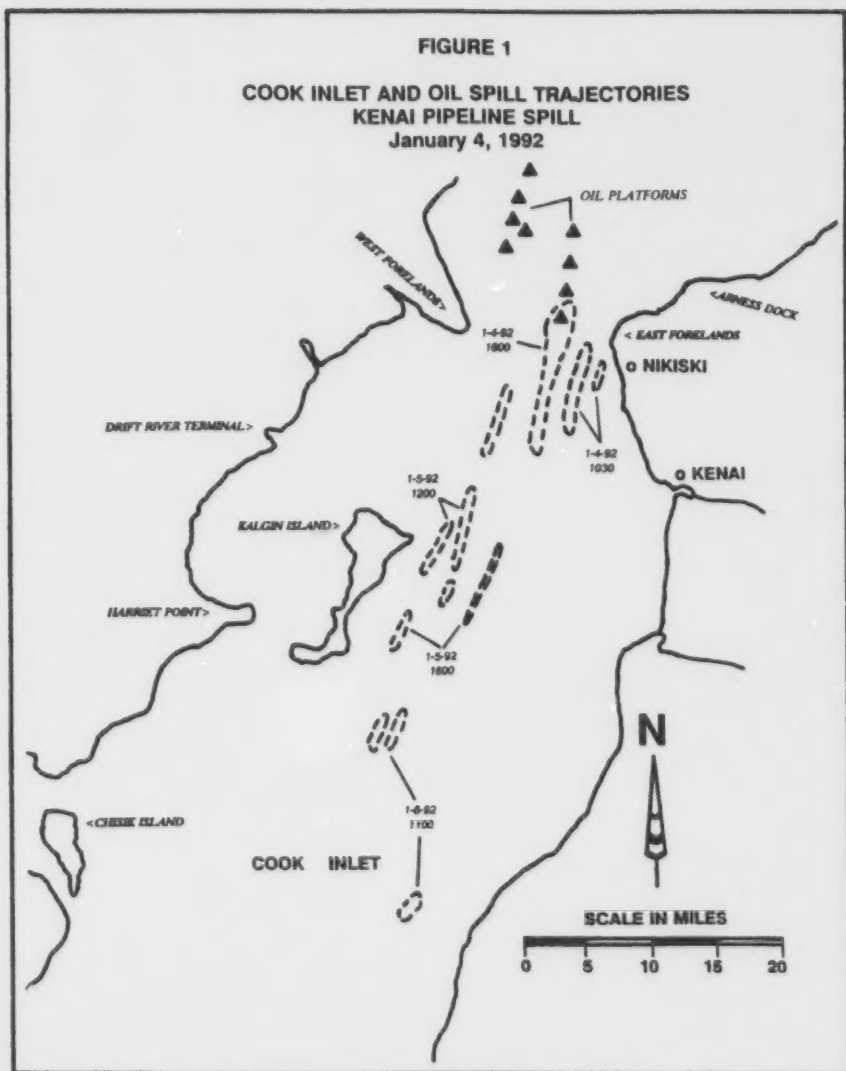
ice in long narrow bands.

At the time of the release, the weather consisted of calm winds, cloud covered skies, air temperatures of between 20 and 25 degrees Fahrenheit, and ice coverage estimated at 10-15 percent in the tidal convergent areas. The daylight hours extended from 10:00 am to 4:00 pm. The release occurred while the tide was flooding, causing the oil to be carried north towards the East Forelands area. For the next several days, the oil spill was tracked as it gradually moved to south-west across Cook Inlet (Figure 1). Under a coordinated command system, plans were formalized by KPL in conjunction with the United States Coast Guard (USCG) and the State of Alaska Department of Environmental Conservation (ADEC) to track, contain, and collect the oil; deploy protective boom for environmentally sensitive areas; perform natural resource damage assessment work; and perform decontamination and demobilization activities. Marine vessels were utilized to tow containment boom, operate oil skimmers, and transport personnel. Numerous overflights of the spill were performed with both helicopters and fixed wing aircraft. A dispersant test was proposed, reviewed, approved, scheduled and attempted, but it proved unsuccessful due to mechanical problems with the application system. By January 6, 1992, the oil had been recovered or dissipated and equipment demobilization began.

Evaluations of the spill response were conducted by several parties. Since this was the largest reported crude oil spill in Alaskan waters since the Exxon Valdez, the evaluations provided a tool to gauge the status and progress of Alaska's preparedness and to identify where additional improvements were needed. Several operations were identified as needing improvement and work is being conducted to address these issues.

The evaluations identified that the greatest success during the spill occurred in the area of spill management. Communications between the involved organizations were smooth and all issues and problems were cooperatively addressed and resolved in a comprehensive and timely manner. The agencies and KPL, although under separate command structures with separate responsibilities, worked in a cohesive team effort to meet the overall goals of the response while satisfying their own objectives and mandates.

This paper discusses and describes the response and management strategies utilized for this spill. These strategies include the formulation of an oil spill response cooperative in Cook Inlet through the pooling of the resources of many oil industries. Extensive pre-planning through the joint development and review of enhanced oil discharge contingency plans, training, spill drills, and continuous evaluations provides the base for the development and further refinement of the strategies. Much of the infrastructure necessary to manage the spill had been developed prior to the discharge because of this pre-planning. The rapid development of a structured management system and



previously developed working relationships between the responding personnel also assisted in the spill. An improved communications system which consisted of radio, visual, and direct personnel interactions led to a cohesive understanding between the actual operation and the command structure.

1. RESPONSE ORGANIZATIONS

KPL is a subsidiary of the Chevron Corporation and seven members of Chevron's emergency response team were immediately mobilized from San Francisco to assist KPL in the management of the spill. These people included a public relations person, a lawyer, and environmental scientists. With the local KPL personnel, this group of people served as KPL's primary spill management organization.

The Cook Inlet Spill Prevention and Response, Inc. (CISPRI) was the primary response contractor for KPL. CISPRI is an oil response cooperative that was formed and is funded by the larger oil facilities operating in Cook Inlet and is composed of both full time response and management personnel and response equipment. CISPRI, as the prime response organization for transporters and producers of crude oil in Cook Inlet, is required under state mandated planning standards to have in their region of operation available personnel and resources necessary to contain, control, and clean up a 50,000 barrel discharge in 72 hours. In addition to providing spill cleanup services, CISPRI committees also serve as planning forums and CISPRI has developed technical manuals to supplement the member companies' plans. CISPRI also provides training to member company personnel in the areas of spill management, spill prevention, emergency response, oil containment and recovery, and health and safety.

CISPRI has a full time staff of 16 personnel and maintains an inventory of a wide variety of marine vessels and cleanup equipment including large open water containment boom, oil skimmers, and nearshore equipment. The CISPRI personnel are highly trained and spill-experienced professionals. During a spill, various contractors may be utilized to supplement the responsible party's and CISPRI's personnel. CISPRI can also gain access to a member company's immediate response personnel. Additionally, CISPRI is now working to establish formal mutual aid agreements with other spill cooperatives and response action contractors.

KPL utilized several consulting contractors for different parts of their operations. Hartech Management, an Anchorage based consulting firm specializing in spill management, assisted in the management of the spill, development of plans, and waste disposal. This consultant had been utilized extensively for spill drills and training for CISPRI and therefore was able to be effectively integrated into the response. Another consulting firm was contracted to perform Natural

Resource Damage Assessment work. An audio/visual presentation company was contracted to perform documentation filming. A third party consultant was also contracted to perform tank gaging services on the recovered oil.

Several cleanup contractors, in addition to CISPRI, were utilized during the spill. These contractors provided both personnel and response vessels. The use of several cleanup contractors provided a level of contracting flexibility for the operations chief and allowed the formulation of many cleanup task forces without overwhelming a single contractor's management personnel. Private fishing vessels were contracted locally to deploy and tow containment boom. It was identified that contracts with vessels in multiple locations of Cook Inlet would need to be established to allow contracting flexibility and to assure year-round availability. Several response management personnel were obtained from the Alaska Clean Seas spill cooperative including three professional radio dispatchers, positions in the command post which formalized and documented all radio communications.

The United States Coast Guard (USCG) is the predesignated lead agency and on-scene coordinator in charge of the incident for the Federal Government under the National Contingency Plan (NCP)². The USCG was active at the command post in the performance of oversight activities and monitoring of the cleanup. The USCG maintained a designated Federal On-Scene Coordinator (FOSC) at their regional office in Anchorage and field responsibilities were delegated to an FOSC representative at the command post.

Other federal agencies involved included a National Oceanic and Atmospheric Agency (NOAA) scientist who served as the Coast Guard's scientific support coordinator (SSC) and was the primary contact point for trajectory analysis and environmental conditions. The SSC had a large amount of local knowledge on Cook Inlet and previous spills which proved very beneficial. Specifically, his experience with the Glacier Bay spill in 1987 assisted greatly during trajectory forecasting. The SSC also assisted with the preparation and evaluation of the dispersant use application. The Environmental Protection Agency (EPA) assisted in the evaluation of the dispersant use application. However, since the dispersant application was proposed for a pre-approved zone³ and since the test application failed, the EPA was not heavily involved in the response. The Department of Interior (DOI) also played a minor role. DOI was contacted to address wildlife concerns, of which there were few at the time of the spill. In addition, the USCG also mobilized members of the Pacific Strike team to the command post to assist in the management of the spill.

The State of Alaska's lead organization for oil and hazardous substance discharges is the Department of Environmental Conservation (ADEC). The predesignated State On-scene Coordinator (SOSC) was located at the regional office in Anchorage and delegated the field responsibilities to the SOSC-field representative. The State Department of Fish and Game (ADF&G) is also

involved in spills to open water and consults with ADEC on wildlife and sensitive habitat areas. All of the ADF&G personnel had been integrated into the spill drills and were familiar with spill response procedures. ADF&G assisted ADEC with the development of protection strategies and Natural Resource Damage Assessment activities.

After the Exxon Valdez spill, the Federal Oil Pollution Control Act of 1990 (OPA 90) established citizens' oversight organizations in two locations of Alaska - Prince William Sound and Cook Inlet. The Cook Inlet Regional Citizen's Advisory Council (CIRCAC) was established in 1990 and has been involved in many aspects of spill planning and response through interaction with the agencies and industries and the participation in spill drills. During the spill, CIRCAC representatives were continually updated and consulted on issues. CIRCAC served as a liaison to other citizen's and environmental organizations. CIRCAC members attended several of the overflights and drafted an evaluation of the response.

2. PRE-SPILL PLANNING

The key element in the success of the management of the spill was pre-planning. ADEC implemented regulations which require oil industries in Alaska to prepare oil discharge contingency plans which must contain comprehensive plans for the prevention, management, containment, and cleanup of discharges of varying sizes that might occur at the facilities including the largest possible discharge⁴. The contingency plans are required to describe the management tactics for the response organization, the equipment and personnel resources to be utilized, and the strategies for implementing their response plans.

The oil discharge contingency plans require the facilities to perform an in depth evaluation of their operation. This evaluation is the key to adequate planning as it allows the facility and agencies to detect flaws in their plans and capabilities prior to the occurrence of the spill. These plans are submitted to the State and reviewed by ADEC, the Department of Fish and Game, the Department of Natural Resources, the local Coastal Zone Management District and Regional Citizen Advisory Councils⁵. The elements of each contingency plan are verified at the facilities through inspections by the ADEC. The ADEC, through response planning standards, has also mandated that minimum amounts of response equipment must be available to contain and clean up each facility's realistic maximum oil discharge⁶. The State of Alaska recently finalized new and more comprehensive oil discharge contingency plan regulations which were developed through public hearings and industry participation.

One of the most beneficial pre-planning activities are oil spill drills. The State of Alaska tests oil discharge contingency plans through spill drills. Many spill

drills, both initiated by the State and by industry, have been conducted throughout the State since the Exxon Valdez. These drills have included the establishment of the company's management teams at an incident command post and the full deployment of response and recovery equipment on the water. Major drills have been attended and evaluated by industry and regulatory personnel from throughout the State.

The spill drills provided opportunities for the evaluation of the operations and management aspects of the mock spill responses and the identification of operational problems in containment and recovery equipment. It also provided an opportunity for the agencies and responding organizations to work together and to build an understanding of each other's personnel, organization, and responsibilities. The drills were accelerated with the requirements of the first few days of a spill compressed into less than a day at the command post. Situations were interjected into the drill by a "controllers group" to add to the realism of the drill.

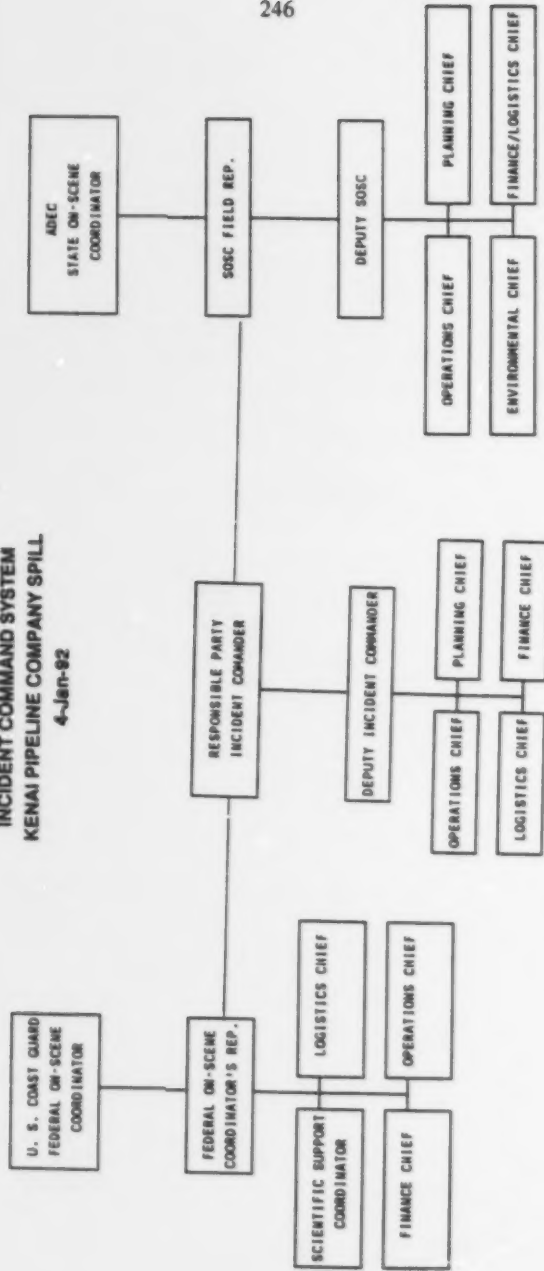
In August 1991, CISPRI conducted a large spill drill in middle Cook Inlet. This drill involved a scenario where a large quantity of crude oil was released from a grounded tanker in Cook Inlet. The drill lasted approximately 12 hours and involved the full establishment of the command center and incident command systems; communications center; aerial surveillance teams; deployment of response vessels and towing of containment boom; deployment and operation of skimming units; and application for an in-situ burning permit.

3. INCIDENT COMMAND SYSTEMS

The responding parties were organized using the Incident Command System (ICS) as illustrated in Figure 2. The rapid establishment of a formal response management structure through an ICS turned the uncontrolled spill into a controlled response. The ICS was originally developed as a management system for combatting forest fires where there are many agencies and local parties involved, various field operations occurring, and complex logistical requirements⁷. The similarities between the requirements of forest fire management and oil spill management led to the adaption of the ICS by many organizations.

The manager of KPL served as the Incident Commander (IC) throughout the spill and maintained the responsibility for committing resources to the spill under KPL. The IC issued all directives to CISPRI. The IC designated the KPL's assistant manager as the Deputy IC. CISPRI management staff were appointed as Section Chiefs for KPL's ICS.

FIGURE 2
INCIDENT COMMAND SYSTEM
KENAI PIPELINE COMPANY SPILL
4-Jan-82



4. COORDINATED COMMAND STRUCTURE

The smooth integration of KPL and the federal and state government was facilitated through the Coordinated Command structure. Under formal ICS systems, a Unified Command structure is utilized where the command staff shares nearly equal authority and the Incident Commander is in charge of the incident including all resources. The Coordinated Command recognizes that the authority is not equal and that all resources are not under one commander, but incorporates the responsible party and agencies in the decision making process.

The Coordinated Command for the spill consisted of the Incident Commander for the responsible party, the FOSC representative, and the SOSC-field representative. Coordinated Command meetings were conducted in a private room, either periodically to discuss the progress of the spill, or when major issues needed to be addressed. All major decisions affecting the response were made at these meetings, thus all major decisions were consensus decisions. Personnel at the meetings were typically limited to only the commanders and coordinators, thus there were no more than six people at one time.

5. COMMUNICATIONS

Personnel communications were also smooth, greatly assisted by the fact that KPL, USCG, and ADEC staff were, for the most part, completely familiar with each other due to the development of first name working relationships through previous interactions at spill drills and other activities. This familiarity also facilitated the resolution of minor issues at lower staff levels, although all major decisions were resolved at the coordinated command level.

The decisions of the Coordinated Command meetings, overflight observations, operations plans, and other concerns were disseminated regularly at command briefings. These meetings were run by the Incident Commander and included input by pertinent members of the command staff. Maps and other visual aids were utilized. The meetings were scheduled for mid-morning to late afternoon (after the first overflights) and late in the afternoon (after the last overflight).

Radio communications had been greatly improved and developed within the CISPRI organization, partly due to the resolution of deficiencies identified in the spill drills. The radio dispatcher greatly assisted in the smooth flow of the radio traffic.

A visual communication tool that proved invaluable with both planning and observations was the use of a professional media contractor to provide video taping and documentation services at the spill. Video footage was collected

during the overflights of the oil slick, recovery operations, and of environmentally sensitive areas. This footage was reviewed later at the command post using a large screen video display system that allowed slow and stop motion playback. This system was a particularly valuable tool for reviewing the slick features and for preparing plans for sensitive environment protective booming, especially for those persons not able to observe during the overflights. A good example of the effectiveness of this tool was where several planners and operational persons reviewed the overflight video footage of a sensitive river mouth in preparation for the deployment of protective boom. The river features were reviewed at the command post and plans formulated by the planners, operational persons, and agencies.

6. SPILL PLANNING ITEMS

Short and long term planning in the spill event were critical elements in the management of the spill and were conducted through the development of Incident Action Plans (IAPs) and general plans. Under standard ICS systems, the IAP is a detailed plan which includes the personnel, equipment, and logistics requirements for each of the proposed operations. In the first stage of a spill response, IAPs are generated by each shift and are then used as a workplan by the following shift. After a spill situation has moved to a less dynamic phase where tasks may be managed as projects, the IAP can be developed and issued on a daily or weekly basis. IAP worked well for previous drills and for this spill.

However, it was determined during previous spill drills that planning for spill responses must extend through the full anticipated length of the spill to be able to adequately manage the spill. In response to this need, the general plan was developed. The general plan details the activities that must occur all the way throughout the final disposition of wastes. The general plan facilitates the forecasting and display of the required operations and resources that will be needed and helps to eliminate "crisis management". The general plan is displayed in a time-line format and is used as a general road map for the response.

The operations, logistics, planning and finance sections all provided input into the development of the IAP and general plans, thus all sections knew the requirements to effectively manage the response and accomplish the goals. The planning section formulated these plans and forwarded them to the IC for approval. All plans were dynamic and were modified as conditions and requirements change.

7. OPERATIONAL ITEMS

In preparation for a spill, CISPRI had purchased several spill response equipment systems that were particularly adaptable for Cook Inlet. A 210 foot spill response vessel is on standby 24 hours a day in the Nikiski area. This vessel was the first piece of equipment to respond and was on scene and skimming in approximately two hours of the release. The vessel had two skimmer systems on board, a Framo Transrec 200 weir type and a Nor-Marine Model 8-14 Foxtail Vertical Adhesive Bank rope mop skimmer. The foxtail skimmer was utilized for this spill because of its ability to skim oil from ice laden waters with minimal interference and because of the lower recovered water to oil ratios. The skimmer was used in conjunction with an oil water separator.

The Foxtail skimmer worked well during the first day while the oil was relatively unweathered. As the oil weathered, the viscosity caused the oil to cake up onto the brushes, significantly decreasing the efficiency of the skimmer. Several techniques to mitigate this problem have been discussed including application of steam and an emulsion breaker onto the ropes and the change-out of the ropes. Further research is needed into this problem.

The deployment of fishing boats was hampered because most of the boats on contract to CISPRI had been dry-docked in Kenai for the winter. This was the most significant operational problem in the response for without these vessels, large amounts of oil could not be swept from the water and concentrated for recovery. Once it was determined that mobilizing the contracted boats would be a problem, CISPRI contracted boats from Homer and Seldovia Harbors, located approximately 70 miles to the south. The time necessary to negotiate and establish contracts further slowed their response. Several of these vessels were not suited for the tasks to be performed (i.e. stern mounted pilot house vessels attempted to tow containment boom from the stern of the vessels) and some of the operators had not been trained or had limited experience in spill response operations which also hampered the efforts. CISPRI is presently working to diversify their fishing boat capabilities and to establish training for the boat operators.

The application of Corexit 9527 was attempted using a helicopter slung bucket application device on streamers of oil that were approaching Kalgin Island. The application failed due to the freezing of residual water remaining in the applicator line from a previous test of the device or from precipitation which may have been pushed up into the nozzles by the wind velocity. Investigations into this problem are continuing.

Centrally located facilities assisted greatly in the management of the spill. A large pre-designated training facility located in Nikiski served as the spill command post. This facility served as the command post for all of the previous large spill drills held in Cook Inlet. The command post was located within three miles of the spill source and CISPRI's response equipment

warehouse, both located at the Rig Tender's Dock. All actual operational activities including the organization and mobilization of cleanup personnel and equipment was conducted at the CISPRI warehouse, away from the command post.

The command post was equipped with the necessary office and communications equipment and was divided into four areas for KPL/CISPRI, USCG, ADEC, and CIRCAC. The KPL/CISPRI area was further divided into the command staff (IC and Deputy IC), logistics, planning, operations, and finance sections. There was also a communications center where radios and telephones calls were managed and where overflight aircraft were dispatched and monitored. Posted in the center of the command post was the IAP and the general plan. Maps and charts displayed the on-water response and operations. Security personnel prevented unauthorized personnel from entering into the command center.

The shared use of resources assisted in the wise use of limited resources. Members of KPL, CISPRI, USCG, ADEC, and CIRCAC were afforded space on overflights of the spill and for transportation to remote areas for beach surveys and natural resource damage assessment work. ADEC personnel also observed on-water skimming and decontamination activities from CISPRI vessels. Coordinated activities such as these also led to more uniform observations and interpretations by all of the parties involved.

8. CONCLUSION

Clearly the best practice for both the oil production/transportation industry and for the regulatory agencies is to place a great deal of emphasis on the prevention of all spills. However strong those efforts are, discharges from facilities will inevitably occur. A detailed facility analysis and the preparation of oil discharge contingency plans is the first step in the formulation of effective spill management strategies. Regulatory agency and citizen group input is a critical step in identifying all concerns in the planning process. Personnel and resources to be utilized in the plan must be well organized and prepared to respond in full force. In areas where industries are in relatively close proximity, the development of spill cooperatives can be the most cost effective manner in meeting immediate response needs.

Management structures should be established in a spill. The use of an Incident Command System for the responsible party and for agencies leads to a greater control of resources and to increased continuity in the total response. A decision making process such as the coordinated command structure facilitates the formulation of consensus decisions and unites all parties towards common goals.

Spill drills are the best tool to critique and evaluate how well plans are established and where improvements are needed. The drills should be as close to a real incident as possible and must include all interested parties. Drills and other preplanning activities build working relationships among the industries, agencies, and citizen groups.

In conjunction with the IAPs, long term planning for the entire length of the spill response is critical in a spill response for all parties. A time line plan such as the General Plan is a proven method for formulating such plans.

Centrally located facilities, shared use of resources, coordinated activities, and the use of video presentations all proved to be invaluable for operations during the spill and should be included in pre-planning for the future responses.

¹ Alaska Oil Spill Commission, Spill, The Wreck of the Exxon Valdez, Executive Summary, Alaska State Legislature, Juneau, Alaska, 1990.

² Federal Register, Volume 50, Number 224, November 20, 1983.

³ Regional Response Team Working Group, Dispersant Guidelines for Alaska, United States Coast Guard, Juneau, Alaska, 1986.

⁴ Alaska Administrative Code, Title 18, Part 75.325.

⁵ Alaska Statutes, Title 46.040.90.

⁶ Alaska Statutes, Title 46.04.030.

⁷ Fire Protection Publications, Incident Command Systems, Oklahoma State University, Oklahoma, 1986.

Will specialized equipment and supplies needed for an oil spill response be available when you need them?

by

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Abstract

During the past few years much high quality technical effort and a significant budget have been devoted to the development of better technologies for responding to an oil spill. Once the current level of interest has passed, will the results of all this effort be available for use in a spill response when you need them? Since medium to large size spills are infrequent events, historically it has been difficult to maintain a stable source of supplies for high-technology oil spill response methods.

It is suggested that it should be an integral component of any oil spill research program to investigate the use of the technology in areas other than spill response. Such a broadening of the utilization base for a spill response technique will assist in ensuring its availability when needed for use at an incident.

Introduction

As a consequence of the *Nestucca* (Owens 1991) and *Exxon Valdez* (Harrison 1991) incidents, there has been a great deal of effort and money expended on the development of new oil spill response technologies. These programs will result in an improved capability to respond to large spills but will the technology be available when needed? While small spills occur quite frequently, medium and large spills occur very infrequently. There are less than 50 oil spills per year with volumes greater than 100 m³ and spills greater than 10,000 m³ occur every 5.6 years on the average.

Techniques for handling small spills are well developed and in most cases the spilled oil is recovered. Medium and larger spills present a greater challenge, and for large spills, less than 25% of the spill material is recovered from the water. Research and technology development are therefore concentrated in improving the efficiency and effectiveness of the response to the large spill situations. New technology is generally developed as the result of hindsight related to a large incident. The problem is whether these technologies will be available or

appropriate for the next large spill which will occur in three to seven years from now. The issue is how can technology and expertise be maintained for the long periods between spills? There are clear economic and social realities that mean that the level of response capability becomes reduced as the time from a spill increases. Oil spill response groups will continue to exercise their capabilities and become proficient in the use of existing equipment. Thus the response to the next large spill will be fought with five year old technology.

Conventional booms and skimmers will continue to be utilised. These are single purpose systems that can only be used for oil spill response. The maintenance of response capabilities based on these tools can be easily accomplished using existing response structures. It is the more complex technologies such as oil spill chemicals, bioremediation, oil spill trajectory models and remote sensing systems that are difficult to maintain in a current state of readiness.

Examples

There was an extensive development of a laser-fluorosensor during the early 1980's. This remote sensing system was developed to allow the detection and identification of oil on water (O'Neil *et al* 1980). It was successfully tested in a number of field programs, and then the priorities of the developing agency changed and further development and commercialization of the system was stopped. A laser fluorosensor would have been very useful for the identification of oil on shorelines during the response to the Exxon Valdez incident, but no laser fluorosensor was available. The prototype system had been removed from the aircraft and various components had been used for other research and development programs.

The use of computer models to predict oil spill trajectories was developed during the late 1970's and early 1980's with many models being generated and used. In a 1983 review article by Huang and Monastero some forty oil spill trajectory models were identified. This review outlines the various algorithms that were used in the models. A contemporary review by Spaulding (1988) indicates little has changed over a five year period. Yet there are a number of efforts underway to develop "new and improved" models which will probably end up to be similar in technique and technical content to those used a decade ago. The only change may be the use of different and probably more powerful computer platforms.

Two currently active areas in oil spill research are bioremediation and in-situ burning. There was a considerable effort in both these areas a decade ago; see (Atlas and Bartha 1972; Westlake and Cook 1980; Tramier and Sirvins (1983); Zobeille, A (1973)) for bioremediation and (Twardawa and Couture 1980) for in-situ burning, and much of the current studies would seem to be a duplicate of previous work.

One of the main components of the international effort on shoreline cleanup techniques during the BIOS project of 1983-86 (Sergy and Blackall 1987) was a study of bioremediation. Scientists from Norway and Canada undertook an extensive program to study the processes and rate of biodegradation in an Arctic environment for both oil and dispersed oil. The use of nutrient enhancement was identified by Elf-Aquitaine (Ladousse and Tramier 1991) and resulted in the development of the oleophilic fertilizer Inipol EAP22. An Arctic study was undertaken in Spitzbergen by Sveum and Ladousse (1989) on the use of this material. So while bioremediation is an "in-study", much of the basic research was done nearly ten years ago.

The initial studies of in-situ burning were undertaken in the early 1980's. Two different types of air-deployable igniters were developed and tested in 1980-81 (Meikle 1981 and Twardawa and Couture 1980). A stainless steel fire-proof boom was designed and tested in 1983 (Buist *et al*), and a major off-shore burn was undertaken in the Canadian Arctic in 1983(Dome). Burning in leads was studied at a meso-scale by Brown and Goodman (1983). This program contained all the aspects of the currently proposed off-shore burn trials now being considered for Alaska, Louisiana and Newfoundland.

Solutions

The duplication of research and the "reinvention of the wheel" seems to be a problem with oil spill response techniques. One of the major reasons for this is the infrequency of large spills and hence a lack of continuity of staff who understand these advanced techniques. This is especially apparent in the regulatory agencies in most countries. The oil spill technical literature is quite specialized and is not readily accessible to the average technical or engineering groups. This literature is generally not "peer reviewed" and is only infrequently available from the broad based computer data sources that are normally used for a literature search. The material that is published outside of the standard oil spill literature is scattered in a number of topic-based journals which are not read by the oil-spill specialists. There are few technical review articles on the subject of oil spills (unless an incident has recently occurred) and this means of initiating new workers in the field is not available. What can be done to prevent this problem in the future?

The format of oil spill exercises and training needs to be changed in emphasis in order to encourage oil spill response staff to acquire a knowledge of new oil spill techniques. Most oil spill response groups hold exercises on a regular basis, and practice the deployment of existing booms and skimmers. These exercises are costly and time consuming to plan and execute. Little or no time is spent during the planning or conducting of such exercises in reviewing and understanding new technology. The success criteria for an exercise is the time taken to deploy the boom and the operational or tactical decisions made with regard to response to the spill scenario. In order that spill response groups be familiar with new techniques, at least one half day of every exercise should be spent in reviewing new techniques and understanding how these may be used in the response area.

The regulatory regime under which oil spill response operates is so designed that it positively discourages the need for or use of new technologies. Most regulations and regulators are confirmed in the "status quo" and actively resist the introduction of new and innovative technologies. The use of in-situ burning or chemical beach cleaners are examples. It should be incumbent on any regulator associated with oil spill response decisions to be familiar with the latest technology and to have an understanding of how these methods might be used in a spill response.

Most oil spill training programs teach only the basics of oil spill response and ignore new or innovative methods. Many of the teachers of these courses do not maintain a familiarity with new techniques and thus these are not presented in the classroom. The instructors in many cases have had limited or no experience at actual oil spills, and have obtained their knowledge second hand. There are notable exceptions to this for those courses that are taught by members of active spill response organizations. The solution to this is for many training programs to include a section on new technologies in their course material and to have this section presented by experts in the field.

Even if the response teams are familiar with the latest in spill technology, there remains the question of whether the equipment and materials will be available for use at the time of a spill. The infrequent need and cyclic funding for oil spill response equipment presents a very difficult business environment for most suppliers of oil spill equipment. This is truly a boom or bust environment which almost guarantees that the supplier will either be out of business or perusing a more stable and profitable activity when the next spill occurs in a few years.

Many of the materials that are used for oil spill response have the potential for use in other areas which could provide a stable business opportunity and thus ensure the availability of the technology when an oil spill occurs. There are probably numerous examples where oil spill technology has optional uses. Three examples

of such a potential are alternative uses for soot-suppressing agents, for oil-thickness measuring systems and oil spill trajectory models.

A significant amount of work has been recently undertaken on the use of chemical agents to suppress the soot associated with in-situ burning of oil (Mitchell 1990). For a suppression of soot by a factor of four-five, about 2% by weight of the material is needed. The chemicals used are not in commercial production and have been custom fabricated in a research laboratory. If this technology were to be adopted as part of the in-situ burning process, it would be necessary to be able to produce these soot-suppressing chemicals on a commercial basis, since it would require about two tonnes of material to treat a hundred tonne spill. It is quite unlikely that this would be a profitable business opportunity and therefore the material would not be available when needed! There are however a number of situations such as flare stacks, pool burning of oil in sumps and test flares which produce large amounts of soot. Studies are now being undertaken to assess the usefulness of the soot-suppressing chemical for these situations. If the chemical can be used on a routine basis for these non oil spill related functions, then the chemical would be readily available for use for in-situ burning during a spill. While such work may seem to be outside of the responsibility of an oil spill research activity, it should be regarded as an integral part of solving the supply problem associated with the oil spill situation.

Significant work has been undertaken on the development of a method of measuring oil thickness. Two methods, one using a laser-acoustic system and the other using passive radiometer (Pearlman et al 1992), have been developed. Both still require field and operational testing. The development of these technologies is expensive, their operation is complex and the purchase cost is high. The market for either or both of these systems for oil spill response is very limited. As with other high technology oil spill equipment, there is some uncertainty whether such equipment will be available when needed for a spill. With the increasing concern for the chronic pollution of the ocean and fresh-water systems, many governments have passed strict legislation regarding the allowable amounts of oil that may be discharged by either a vessel or a facility. The penalties associated with these laws are frequently a function of the amount of oil spilled. The oil thickness sensors could be used to determine this volume, and hence would be deployed on a routine surveillance basis. These legal needs may supply a suitable opportunity to develop a sustainable business function related to providing either equipment or airborne service for remotely measuring oil volumes. Should this occur, the same technology would be readily available in the case of a major spill.

Much effort has been spent on the development of trajectory models to predict the motion of spilled oil on water. Most of these models needed spatially and

temporally spaced wind and ocean current fields for the model domain and during the forecast interval. In order to generate such data, complex oceanographic models (Backhaus, 1985; Blumberg and Mellor, 1999 and Hirt et al 1983) must be available and running in real-time. Since oil spills occur quite infrequently, it is not feasible to do this on a real-time 24-hour basis. Similar data is needed for use with real-time search and rescue models. Since the search and rescue function is more frequently needed than oil spill model data, it would seem reasonable that the needs for wind and current data for search and rescue purposes be used for oil spill models.

Conclusions

The small market and the long time between major oil spills mitigate against the use of high technology or specialized equipment during a response. Rather than force the oil spill response funding groups to bear the burden of maintaining expensive systems for response to unlikely events, the onus should be placed on oil spill technology research groups to investigate alternative users for their technologies.

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THE MSRC RESEARCH AND DEVELOPMENT PROGRAM

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ABSTRACT

Implementation of an active research and development (R&D) program is one of the chartered missions of the Marine Spill Response Corporation (MSRC). Design and sponsorship of projects is in keeping with the concept of best effort inherent in the operations of MSRC, based on the premise that enhanced knowledge and technological development will improve future response capabilities. A detailed priority setting exercise was carried out, involving extensive consultation with the oil spill R&D community. The MSRC R&D program is now fully activated, with projects underway in the areas of remote sensing, *in situ* burning, dispersants, oil/water separation, spilled oil properties, countermeasures effectiveness and bioremediation. The program stresses cooperation with other R&D sponsors, and has started an active information dissemination process.

INTRODUCTION

The Marine Spill Response Corporation is a not-for-profit, non-membership corporation. It was chartered in August 1990 to respond to large oil spills in coastal and tidal waters, and certain inland waters, of the United States. MSRC intends to render its best effort with the capability it will possess to contain and clean up catastrophic and other oil spills for which it is called out. The concept of 'best effort' includes the sponsorship of research and development activities for the purpose of enhancing future response capabilities. Inclusion of an R&D program in the chartered activities of MSRC had its origin in industry plans for a national organization able to respond to catastrophic oil spills (American Petroleum Institute 1989, PIRO Implementation Subcommittee 1990).

Oil spill pollution and response has been a topic of active study in North American and other oil-producing countries for many years (National Research Council 1985, Office of Technology Assessment 1990, International Maritime Organization 1992). The need for better methods and strategies for responding to and cleaning up oil spills has been

heightened by several recent major tanker accidents, oil spills in the Arabian Gulf area, increased requirements for oil spill response plans and preparedness for spill response, and the strengthening of international accords for tanker safety and spill response. Additionally, the rules currently being drafted under the U.S. Oil Pollution Act of 1990 may provide direction that future increases in response capability should be met by innovative countermeasures, additional to the conventional mechanical clean-up methods now in use. Public and private organizations in the U.S. and abroad are responding to these initiatives by increasing their internal oil spill R&D activities and budgets, and by actively seeking collaborative opportunities to enhance such efforts.

The Marine Spill Response Corporation supports an R&D program with a currently planned annual budget averaging \$7 million over the first five years of operation. Research and development is considered a key element to improving future capability of responding to spills of oil and oil products. However, oil spills at sea and in coastal waters are complex and sometimes massive events and it would be unreasonable to assume that all of the diverse problems associated with oil spills and spill response will be resolved.

PRIORITIES PLANNING

An initial step in developing the R&D program in MSRC was to review the priorities considered by other organizations and identify those projects or project areas that also fall within or otherwise might complement the R&D activities germane to the MSRC mission. This review began with a list of priority R&D topics identified by the Petroleum Industry Response Organization (PIRO), published as part of a report in January 1990. Similar priority lists from other sources were also reviewed. Technical representatives of the agencies and organizations performing spill response R&D were interviewed to: 1) better identify practical R&D needs of the oil spill response community (the users of the results of the R&D); 2) determine the technical background and rationale for some of the R&D projects identified as being especially important; 3) identify R&D issues that have already been addressed but from which the results have not yet been widely disseminated; 4) identify those projects that are underway or for which partial or complete funding has been committed; and, 5) identify those projects and agencies or organizations with potential for collaborative R&D relationships with MSRC. A large number of productive contacts were made with individuals and organizations involved in oil spill R&D, leading to a deliberated priority list of program areas and projects to guide the MSRC R&D effort. The plan was published as a technical report (Marine Spill Response Organization 1991).

It is important to realize that such a priority list is a dynamic planning instrument that will be revised periodically as new information becomes available. In any case, MSRC is committed to review the priority matrix

yearly, assisted by its system of technical advisory committees, and in response to results from ongoing projects and external evolution of both operational needs and new technologies.

PRIORITY R&D TOPICS

A total of 96 topics and subtopics were identified as important to the MSRC R&D program. These are listed in outline in Table 1 and are now being implemented, although not all of the topics are being worked on at once. The current R&D activities are driven by a particularly immediate need for results, as well as opportunities for effective collaborative work with other R&D sponsors.

Ongoing study areas fall into seven main categories, all of which provide potential opportunities for enhancing spill response capacity. These include:

- enhanced remote sensing capacity of oil spills, allowing detection of oil, and especially thick oil, on a day-night basis, under adverse weather conditions, and integrated with MSRC's incident command system to provide real-time guidance to spill responders for optimizing response tactics;
- development of in situ burning as a countermeasure, emphasizing both operational and environmental safety, as well as developing technologies which allow the potential response method to be effective under the range of ocean conditions in which oil spill response needs to be executed;
- the use of dispersants as an early countermeasure, a multi-faceted topic which needs further attention with regard to improved application technologies, use on heavy and emulsified oil, selected critical environmental effects studies and field demonstrations of effectiveness;
- determination of the performance capability of mechanical response equipment beyond name plate capacity claims, so that response planning and operational decisions can be optimized over the range of environmental conditions under which response to large spills may need to be executed;
- treatment and storage of recovered materials, in particular oil-water mixtures, including oil-water separation systems for vessels of opportunity used in oil spill response, treatment of solid oily wastes and systems to enhance storage of recovered materials;
- methods of breaking emulsions in an operationally relevant fashion, which would also be environmentally acceptable, to address the problem in relation to in situ burning, dispersant effectiveness, mechanical recovery, and oil-water separation; and,

TABLE 1: Summary of Oil Spill Response R&D Priorities Under Consideration in the MSRC Program

Topic Category	Project Area
Prevention of Loss of Oil from Tank Vessels	Onboard Countermeasures Booms Spill Treatment Agents Chemical Containment Rapid Response Systems
	Shipboard and Shoreside Human Factors and Training
	Decision Support Systems for Oil Spill Emergency Management
Oil on Water Countermeasures	Surveillance
	Laser Fluorosensor
	Microwave Radiometry
	UV/IR Systems
	Radar Systems
	Data Management
	Satellite Surveillance
	Shipboard Slick Detector
	Submerged Oil Detection
	Oil Under Ice Detection
	Slick Tracking Linkages
	ICS Integration
	Booms
	Oil on Icy Waters
	High Current Devices
	Computer Assisted Design
	Mesoscale Testing
	Skimmers
	Icy Waters
	Oil/Water Separation
	Pumps
	Recovery Systems
	for Viscous/Waxy Oils
	Fishnet Skimming Barrier
	Mesoscale Testing

TABLE 1 - continued

	<i>In Situ</i> Burning
	Airborne Plume Behavior
	Emulsions
	Environmental Effects
	Waves and Currents
	Mud Flat Applications
	Field Verification
	Recovered Materials Management
	Oil/Water Mixtures
	Chemical Dispersants
	Heavy Oil Constituents
	Effectiveness Testing
	Dispersion Physics
	Other Treatment Agents
	Aerial Application
	Dispersion of Thick Slicks
	Modeling Fate/Degradation
	of Dispersed Oil
	Dispersants for Shorelines
	Sorbents
	Effectiveness Test Methods
Mitigation of Shoreline Impacts	Bioremediation
	Effectiveness Tests
	Application Methods
	Field Tests
	Chemical Washing
	Solvent Washing
	Water Washing Methods
	Recovered Materials Management
	Oily Solid Materials
	Sorbents
	Effectiveness Test Methods
	Wildlife Deterrants
	Alternative Protection Methods

TABLE 1 - continued

Environmental Fate and Effects	Physical and Chemical Fate Physico-Chemical Properties Surface Trajectory Models Subsurface Oil Movements Shoreline Fate Model Ocean Surface Circulation
	On-Scene Analytical Chemistry Biological Effects Intertidal and Subtidal Vegetation Intertidal and Subtidal Animals Bioavailability of Hydrocarbons in Sediments and Beach Soils Wildlife Pathology Biological Effects of Bioremediation Effects of Oil on Fishery Species
	Long-Term Fate/Effects of Dispersed/Undispersed Oil
	Identification and Monitoring of Bird Species/Endangered Local Populations
	Historic Spill Studies for Predictions of Long-Term Effects
	Sensitive Ecosystem Identification
	Endpoint Definition for Response
	Relative Ecological Effects of Different Shoreline Responses
Human Health and Safety	Occupational Health Effects Contamination of Fisheries Species

Source: Marine Spill Response Corporation 1991

- comparative evaluation of the ecological effectiveness of shoreline countermeasures, to allow optimization of critical but limited response resources, which includes understanding of the direct effects of oil, the effects of shoreline countermeasures as used in previous spill circumstances and the use of bioremediation as a low impact countermeasure.

Most if not all of these priority areas require some evaluation in the field, on the sea or on marine shorelines. The MSRC R&D program is actively pursuing possibilities for test spills, carried out under conditions which would allow both scientific and environmental control of such studies.

COOPERATIVE RELATIONSHIPS

One of the important goals of the R&D program in MSRC is to catalyze the R&D community to achieve a better coordinated effort through the establishment and maintenance of an extensive network of R&D practitioners. This is being made possible on the one hand by the importation of already established personal professional contacts of the staff hired in the MSRC R&D division, secondly by an active program of consultation to enhance this network (mechanisms in place to achieve this include the MSRC R&D Advisory Committee and the Marine Pollution Association R&D Technical Staff; both provide effective support for the MSRC R&D program), and thirdly by more formal agreements for R&D cooperation between MSRC and organizations with similar interests.

The benefits of cooperation among the practitioners of oil spill response R&D fall generally into four interrelated categories: enhanced general information exchange to assist individual R&D funders and implementers by a more rationalized program design; provision of expert collegial assistance in the execution of R&D projects; opportunities for transfer of technologies ready for further development to solve oil spill response problems; and, enhancing the overall cost effectiveness of programs by minimizing duplication, planning complementary programs, and potential cost sharing when project objectives are similar. The degree of cooperation among parties might extend to all elements, although free information exchange alone is already a benefit.

Project specific agreements have been reached with: the National Oceanographic and Atmospheric Administration for studies on shoreline cleanup effectiveness in Prince William Sound after the *Exxon Valdez* spill and for participation in the Arabian Sea cruise of the oceanographic research vessel *Mt. Mitchell* to evaluate the environmental aftermath of the Gulf War oil spills on the shorelines of Saudi Arabia; the Minerals Management Service in support of oil spill drifter studies as part of a spill experiment in the North Sea; the American Petroleum Institute for a feasibility evaluation of a spill test at a United States coastal site; the

Smithsonian Institution for definitive evaluations of the effects of two oil spills in Panama on coral and mangrove ecotomes; Alaska Clean Seas, Minerals Management Service and others on *in situ* burning; Environmental Protection Agency/National Environmental Technology Applications Corporation for the establishment of bioremediation test methods; Environment Canada and the Canadian Petroleum Association for ten separate spill response technology studies; European Space Agency for oil spill sensing system evaluations. New collaborative work being planned includes remote sensing system developments, *in situ* burning equipment, dispersant effectiveness, effects and application trials, bioremediant tests in saltmarshes, oil-water separation equipment and demulsification. The potential list of projects is long.

Action is being taken to implement a memorandum of understanding for cooperative R&D signed on March 26, 1992 in Austin. There is much commonality in the priorities areas identified by the two organizations and good promise of productive cooperative R&D for years to come, addressing response-related issues of relevance to the State of Texas and MSRC's Region III, as well as oil spill response needs more generally. Memoranda of understanding for programmatic cooperation are also being developed for implementation with the Minerals Management Service, the California Department of Fish and Game and the United States Coast Guard, as well as internationally with, CEDRE in France, the United Kingdom Marine Pollution Control Unit, and other organizations.

The promise for the effectiveness of cooperative relationships among the practitioners of oil spill related R&D is high, and in keeping with the magnitude of the task of solving the major issues which still prevent recovery of much of the oil from large spills in marine and coastal environments. There seems to be a new age for science and technology developments in this area of industrial endeavor which can derive benefit from developments in other science and engineering disciplines. Almost by definition this will require active and open cooperation among the interest parties such as that enhanced by the ongoing efforts of the MSRC R&D division.

INFORMATION TRANSFER

It is the intention of MSRC to publish the results of R&D programs funded by MSRC in appropriate scientific and technical journals, technical reports, and public information documents. The intent is to make this information available to oil spill response personnel and organizations world-wide, irrespective of affiliation. However, when R&D projects are directed at developing commercial processes or products, appropriate contractual mechanisms will be used to create and protect intellectual property rights to optimize their potential for commercialization, which is an approach consistent with MSRC's charter and mission.

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New Test Basin for Experimental Studies on Oil Spill in Ice

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Abstract

Hamburg Ship Model Basin (HSVA) has converted one of its ice tanks into an Environmental Test Basin (ETB) for cold regions. Conversion was started in 1991 and completed in early 1992.

Dimensions of the test basin are: 30 m long, 6 m wide and 1.5 m deep. Special ETB-features are, besides the ice making facilities (2 mm/h ice growth), a mobile wave generator and a current device which is used together with a longitudinal bulkhead to operate the test basin as circulating water channel.

A joint industry research program has been proposed to investigate weathering, fate and spreading of various oils in different ice conditions with and without currents. Laboratory testing will also be dedicated to the development of suitable combat techniques for oil spills in ice covered areas.

1. Introduction

Oil spills in open water have been investigated for many years and combat equipment has been developed and operated successfully. Like in many other cases, new ideas will evolve in order to respond more quickly and more efficiently to the various types of oil spills. The new Environmental Test Basin of HSVA is a useful tool for development of the next generation of oil spill equipment.

Much more unresolved are the cases in which oil spills occur in ice covered waters where the various ice conditions are an additional

parameter. Problem areas are spreading and migration of oil in ice, separation of oil from the ice, as well as weathering and fate of oil under icy conditions.

So far, burning of oil has been the main combat method in case of oil spill in ice covered areas. For this purpose special ice management techniques to trap the oil in burnable quantities are to be developed.

A joint industry research project has been proposed by HSVA in order to investigate weathering, fate and spreading of various oils in different ice conditions with and without currents. Laboratory testing will, also be dedicated to the development of suitable combat techniques for oil spills in ice covered areas.

2. Description of Test Facilities

2.1 Test basin

The Environmental Test Basin (ETB) consists of a three-part concrete basin with trim tank, testing tank and oil recovery pit, which is also used for melting of the ice. The actual testing tank is 30 m long, 6 m wide and 1.5 m deep. It can be separated by trap-doors from adjacent test rooms when ice conditions with cold air temperatures are to be simulated. Fig. 1 shows a view on the testing tank with circulating channel (see paragraph 2.3). The oil recovery facilities are seen at the rear part of the tank.

The concrete walls of the test basin have been treated with a special

HSVA**HAMBURG SHIP MODEL BASIN**

Fig. 1: HSVA's Environmental Test Basin (ETB) with longitudinal bulkhead, propeller drive and baffles for circulating flow tests (oil/water coalescence separator seen at the rear)

coating which does not affect bacteria in case special tests are carried out to investigate biological combat methods.

A motor-driven carriage runs along rails on the basin walls (max. speed = 2 m/sec). An hydraulic lifting gear is installed such that it can be operated at any location of the test basin. Direct observations of the tests from below are possible thru windows in the bottom of the tank. Furthermore, visual observations are recorded by an underwater video system which consists of two miniature underwater color video cameras, uw-searchlights, mixing desk with typewriter and stopwatch, monitors and recorder.

A transverse bulkhead can be installed at three different positions of the basin in order to keep part of the tank filled with water and drain the other part. A separate storage tank below the testing basin provides for containment of 120 m³ of tank water. It is used e.g. as buffer store in connection with oil/water separation. A water pumping system combines the test basin with the oil recovery/ice melting pit and with the storage tank. Initially, the tank was filled with water of 3.0 % salinity (NaCl) to simulate sea water.

Safety against explosion, particularly when testing crude oil, is provided by methane gas detectors and by forced air exchange devices which are installed in the testing tank.

2.2 Simulation of ice conditions

The cooling system of the Environmental Test Basin has a capacity of 42 kW which is transferred into the testing room via ceiling coolers uniformly distributed over the whole tank. The air temperature can be set

as low as -18°C and can be kept constant within 1°C .

The ice grown on the water surface represents sea ice according to the tank water salinity of about 3 %. The tank water can be kept close to the freezing temperature (about -1.8°C), thus providing an immediate start of ice growth as soon as the air temperature is lowered. Due to a well adjusted freezing process a uniform ice growth of max. 2 mm/h is achieved over the entire tank length.

Typical sea ice conditions which can be simulated are:

- * homogeneous level ice of constant thickness
- * brash or pack ice fields
- * rafted ice (level ice layers rafted upon each other)
- * pressure ridges (longitudinal ice features consisting of broken ice pieces pressed together, thus forming above water sail and underwater keel)

After completion of testing the ice is pushed over a weir into the oil recovery and ice melting pit where the oil is separated from the tank water after melting of ice.

2.3 Current device and wave generator

The testing basin has been equipped with a horizontal circulating flow channel as shown in the photograph of Fig. 1 and in the plan view sketch of Fig. 2.

A longitudinal bulkhead separates a 3 m wide channel from the basin. The water depth in the channel is 1 m. At both ends of the bulkhead

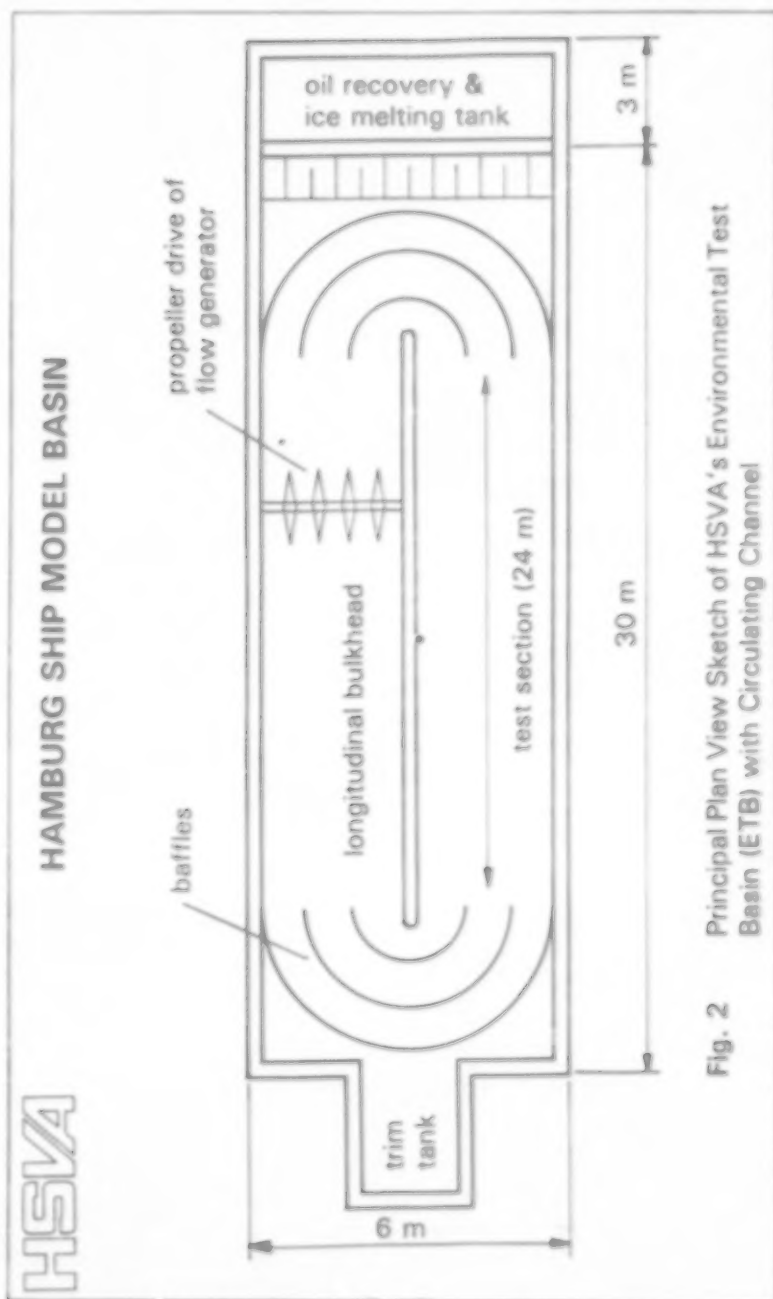


Fig. 2 Principal Plan View Sketch of HSVA's Environmental Test Basin (ETB) with Circulating Channel

semicircular baffles out of rolled stainless sheet steel are installed to guide the flow. At the beginning of the actual test section straightening blades provide for uniform flow distribution. The current generator consists of four propellers (see Fig. 1), driven by electric motors of 20 kW total capacity. Impeller wing wheel sensors are used to control the current speed, which reaches a maximum of 1 m/sec (about 2 knots) at a channel width of 3 m. Higher current speeds can be achieved by decreasing the cross-sectional area of passage.

A mobile wavemaker which operates on the plunger principle can be installed in the foremost part of the testing tank. The maximum height of regular waves at 1 m water depth is approx. 15 cm.

2.4 Measuring equipment

The testing tank is equipped with PT 100 temperature sensors to control the air and water temperature and with impeller wing wheel sensors to control the current speed. The sensors are registered by a data logging system which either records in digital form on floppy discs or presents real time analogue data on a color printer. Fast data acquisition is carried out via 486 PC and analogue/digital converter.

2.5 Oil recovery devices

After completion of testing the oil on the tank surface or possibly a mixture of oil and ice is being skimmed by means of mechanical skimming devices into the oil recovery and ice melting pit at the rear end of the basin (see Fig. 2). For removal of the oil from the testing tank mechanical skimming devices plus a vacuum absorbing and pumping

device is used. For final cleaning of the testing basin and equipment a superheated steamcleaner is applied.

The separation of tested oil from the oil/water/ice mixture collected in the oil recovery pit is accomplished by a coalescence separator. The pumping capacity of the separator ranges from 1 thru 8 m³/h, depending on the viscosity of the oil. The separator has an oil storage capacity of 0.3 m³. The separated water, which has a residual oil content of less than 20 ppm, is being pumped into the buffer storage tank below the test basin. After the oil recovery and cleaning of test equipment has been accomplished the water is pumped back into the testing tank.

Special containers are used to store different types of crude and other oils for testing purposes.

3. Topics of Proposal for Joint Industry Project

A joint industry research project is proposed by HSVA in order to investigate weathering, fate and spreading of various oils in different ice conditions with and without currents. Laboratory testing will also be dedicated to the development of suitable combat techniques for oil spills in ice covered areas.

In particular, the experimental program of the joint research project will cover the following major topics:

- * investigation of spreading and adsorption processes of crude oil and oil products in ice covered seas with and without currents

parameters to be varied: type and amount of oil, ice conditions, current speed

- * degradation of oil in ice
- * investigation of ice management techniques in different ice conditions in order to prevent or limit oil spreading and to facilitate removal of oil
- * development of techniques and equipment for separation of oil and ice
- * application of dispersants on different types of oil with and without sea current
- * testing of biological combat methods
- * development and testing of special combat equipment for oil spills in ice

Of course, a wide range of other tests can be carried out in the environmental test basin, e.g. on methods to combat 'chocolate mousse' and other phases of oil at controlled temperature conditions in non-ice covered seas. Finally, it is intended to provide the basis for the development of contingency plans.

THE ALASKA COASTAL COMMUNITIES COOPERATIVE: THE CONCEPT AND FEASIBILITY

by

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1 INTRODUCTION

In recent years there has been a worldwide effort to develop the capability to respond quickly and effectively to oil spills. Alaska has been part of this effort; indeed, it is not an overstatement to say that Alaska has been on the leading edge of this movement. During this time, Alaska's readiness to respond to oil spills has been greatly enhanced through the efforts of government, industry and residents. This extensive effort in time and dollars has resulted in a much better understanding of Alaska's needs, and the recognition that oil spill response capability is not fully realized in Alaska.

Two areas of specific needs have been identified, namely shoreline protection and nearshore response, and response to non-crude spills. This paper reports on a new initiative to further prepare Alaska to deal with spills in the future by focusing on these needs.

In late 1991 the Prince William Sound Regional Citizens' Advisory Council commissioned a feasibility study for a community-based oil spill cooperative and an associated spill school. A draft report was completed for the RCAC in January of 1992 and the final report has just been submitted. This paper describes the concept of the Alaska Coastal Communities Cooperative as presented in these two documents.

The existing network of oil spill cooperatives (the Cook Inlet Spill Response, Inc. (CISPRI) in Cook Inlet, the Ship Escort and Response Vessel Service (SERVS) in Prince William Sound, and the Alaskan Clean Seas (ACS) in the Arctic) have developed tremendous capability to respond to oil spills in Alaska. SERVS, with good reason has expended great efforts towards initial response in the vicinity of the spill site. The recovery of every gallon of oil is one less gallon of oil to threaten the coastline, but as we have seen from past spills, that even the best prepared and trained organization cannot hope to contain all of the oil that may escape from a stricken vessel. Some emphasis has been placed on shoreline protection and nearshore response with strategic placement of equipment depots and training of local personnel, but the local communities believe more emphasis is required for the protection of coastal communities and the natural resources of coastal waters that they depend on from oil spills.

The central thrust of the report was the design of an organization that will makes use of the local communities personnel and resources to protect coastal resources. Coastal communities have made it quite clear that they are willing to provide assistance and resources to shoreline protection and nearshore recovery. As one person put it, "It's not a question of whether to get local citizens involved in spill response, but how to do it. They're going to be there, the *Exxon Valdez* proved that."

To bolster the protection SERVS offers, residents of coastal communities have repeatedly raised the idea of creating a coastal communities cooperative. The need for more coastal protection has also been recognized on state and federal levels. The Alaskan legislature recognized this when it passed SB 264, which mandates the establishment of local equipment depots and a local response corps. The express intent of the law was to create the structure and means by which fishermen and other local residents could bring to an oil spill response their considerable equipment, knowledge of local conditions, and their commitment to protecting coastal resources. The federal Oil Pollution Act of 1990 similarly requires that oil spill response in Prince William Sound include the mobilization of local resources.

The past spill responses have shown the inefficacy of negotiating individual response contracts with local resources and/or waiting until after a spill has occurred to organize local resources. The Alaskan Coastal Communities Cooperative (ACCC) would organize local resources and provide appropriate training, equipment and coordination to deal with both small spills, local product spills and catastrophic spills. In doing so, it would also help satisfy the requirements of both state and federal law.

II THE NEED FOR THE COOPERATIVE

Although Alaska has a good network of oil spill cooperatives, oil spill contractors, and a tremendous inventory of equipment; the protection of shorelines and nearshore response with local personnel and resources has no greater applicability than in Alaska. Oil spill contractors can be hired to fulfill these roles, but based on economic comparison alone, the cost of using the local resources established in the spill area versus the importation of large amounts of men and equipment would seem to be attractive. To further advance the need for a coastal communities cooperative, the recognition of an enhanced oil spill response due to the use of local knowledge of the area combined with technical expertise of the industry, would provide greater protection for Prince William Sound.

The report identified several problems that need to be solved to respond to the need for better oil spill protection for shoreline and nearshore areas. The problems identified are:

1. The risk of major crude oil spills in coastal Alaska will be reduced by prevention requirements, but still exists and today is only partially addressed.
2. The risk of refined oil product spills in coastal Alaska has not been adequately addressed at this time. See A.D. Little, "Study of Non-Crude Tank Vessels and Barges," Task 4 - Response Organizations and Depots (July, 1991).
3. To date, industry planning and response efforts for potential crude oil spills have focused heavily on containment and removal at the spill site, rather than shoreline protection and nearshore response. Greater emphasis needs to be placed on shoreline protection and nearshore recovery, especially since past history indicates that site responses are only partially successful.
4. The primary spill response organization in Prince William Sound, Alyeska's SERVS division, will release control of a major spill response within 72 hours after the spill, that is relinquish spill management and operations to the company whose tanker caused the spill. Thus, there is a need for an operational structure to bridge the transition from SERVS management to management by the responsible party.
5. State funds derived from taxes on crude oil production and earmarked for the creation of a statewide system of oil spill equipment depots and local response corps have yet to be used for these purposes.
6. Local resources that can effectively participate in spill response have not yet been effectively trained, equipped or organized to achieve their maximum effectiveness on either small spills or major crude oil spills.
7. Although some oil spill equipment and resources have been stored by industry in local communities, the ability to rapidly deploy this equipment has not yet been demonstrated.
8. Although the level of technical expertise available in Alaska has greatly increased in the past few years, there is not yet an effective system in place to augment that expertise with local knowledge to maximize the effectiveness of spill response in all regions of the state.
9. Environmental and economic considerations will influence future oil spill response activities more than they have in the past. Far from being a burden, however, incorporation of these concerns into spill response will enhance the success of response activities while simultaneously minimizing environmental harm and the resulting damage claims.

10. Section 5005 of the Oil Pollution Act of 1990 requires the pre-spill positioning of response equipment and a hatchery protection program in Prince William Sound, as well as the establishment of an oil spill response organization. OPA '90 also requires oil spill response training for the residents of Prince William Sound and the local fishing industry. The act requires practice exercises to test the effectiveness of the equipment and personnel described in oil spill contingency plans.

Sections 4201 and 4202 of OPA '90 clearly mandates a response capability greater than that needed for an *Exxon Valdez* spill size. Equally clear, no existing organization in Alaska has yet met that requirement.

There are undoubtedly a number of ways in which to solve each of these ten problems. The advantage of establishing an entity like the ACCC, as proposed in the report, is that the ACCC can be used to solve all of the above stated problems.

To solve the stated problems, the report established ten objectives of the ACCC, these are:

1. To provide a mechanism for harnessing the considerable energy, resources, knowledge, and commitment of local residents to enhance oil spill response capability in coastal Alaska.
2. To leverage industry funds and resources with government funds and resources and vice-versa. For example, rather than having government and industry establish separate equipment depots for crude and product spills, a common, well-managed pool would serve both and create a greater unified response capability.
3. To develop an equipment inventory and operating base to permit the existing local resources to be utilized to their maximum capability.
4. To develop the capability to carry out shoreline protection and nearshore response activities in support of response to crude oil spills in Prince William Sound, Kenai Peninsula, Kodiak, and surrounding areas or coastline potentially affected by the TAPS trade.
5. To train the core staff and the reserve staff of local residents, fishermen and vessel operators in oil spill control technology, the National Institute of Incident Management Systems - Incident Command System (NIIMS-ICS), Hazardous Waste Operations and Emergency Response (HAZWOPER), and marine firefighting so they will be qualified to participate in oil spill responses.

6. To participate in oil spill response activities for catastrophic crude oil spills by providing shoreline protection, nearshore response and other appropriate actions for which the ACCC is equipped and trained. These activities would complement the activities of existing cooperatives, with the ACCC acting as a response action contractor on behalf of SERVS, CISPRI, a member company, the state of Alaska or the federal government. ACCC's participation in these spills would be pursuant to NIIMS-ICS guidelines.
7. To develop a data base of and a contractual relationship with operators of fishing, charter, and other vessels to provide support vessel service during a spill response.
8. To serve as the contracting entity to dispatch support vessel services to SERVS, CISPRI, or member companies.
9. To develop a Response Plan to guide ACCC's response actions.
10. To develop response capability to non-crude product spills in whatever portions of the state deemed appropriate.

The fulfillment of these objectives would substantially improve the state of readiness for oil spill response in Alaska and result in a substantial increase in spill performance.

III ADVANTAGES OF THE ACCC

In designing the organization of the Alaskan Coastal Communities Cooperative, the author found several advantages that the creation of the ACCC offers, not only to industry, but to state and federal officials and the State of Alaska. As a supplement to existing oil spill control activities, the creation of the ACCC would generate a number of advantages.

1. The total level of oil spill response capability in Alaska would be significantly enhanced in two ways. First, all appropriate local resources will be put to use. Secondly, the ACCC will ensure that the response equipment it acquires is compatible with existing resources, thus creating maximum response capability at minimum cost. For example, there are skimmer heads that use seiner vessel hydraulics and small barges for storage of recovered oil that can be towed and serviced by seiners.
2. Industry funds and resources can be leveraged by government funds and resources. For example, rather than having government and industry establish separate equipment depots for crude and product spills, a common, well-managed pool would serve both and create a greater unified response capability.
3. Trained, equipped and effectively managed local resources can respond more quickly to a spill, thus limiting the spread and

impact of the spill, which reduces the environmental and economic damage and cleanup costs.

4. Greater public trust will be generated to the benefit of both industry and government when an Alaskan based response entity is created because the public will be assured that local resources will be effectively used in protecting local coastlines, and because the public will participate in governing the ACCC through representation on its board of directors.
5. Costs for the ACCC's response would generally be substantially lower than a contractor's bill for the same efforts. This is because ACCC's core personnel would be billed at regular payroll rates, supplies are generally billed at cost, equipment is not generally charged for except for repairs, and the non-profit status creates no reason to overcharge a client.
6. A separate organization like the ACCC can easily initiate action in parallel with other response organizations. For example, while a primary response group is fully engaged in recovery activities near the spill site, the ACCC can simultaneously be carrying out shoreline protection activities.
7. If contract vessel support services are provided to both parties by a third party such as the ACCC, response activity is less likely to be interrupted when spill management passes from SERVS as an initial responder to the spiller.
8. The ACCC can provide a combination of local knowledge and technical knowledge that will augment the expertise of the spiller or its contractors, which will markedly improve response efforts. Furthermore, locally developed data bases of response capabilities are likely to be more accurate than externally maintained data bases.
9. The existence of a permanent organization like the ACCC will alleviate the serious problem of loss of knowledge and experience acquired during a spill.
10. Logistics bottlenecks can be minimized by the dispersed pre-positioning of equipment. With trained responders and equipment available throughout Prince William Sound, Kenai Peninsula and Kodiak coastal areas, response activities can be initiated with greater speed and can be carried out when they would otherwise be constrained by weather or transportation limitations.
11. The ACCC can assist industry in fulfilling the contingency planning and spill response requirements of HB 567, as well as OPA 90's requirements for mobilization of local residents and vessels.

12. The ACCC provides a mechanism for the state to fulfill its mandate to create local response corps and equipment depots, and its need for training state government staff and local response corps.
13. Creation of the ACCC could increase the support for and likelihood of the legislature passing acceptable responder liability relief in 1992.

IV. PREVIEW OF THE ACCC ORGANIZATIONAL STRUCTURE

A non-profit corporation is the likely organizational structure for the ACCC. A management board appointed from the contributing participants and public groups is envisioned. This board would set the policy and budget of the organization. A separate technical advisory board would be appointed to deal with equipment selection, training requirements, technical aspects of response, and evaluation of drills and response activities. The board would hire the director who will manage the ACCC on a day-to-day basis and serve as its spill response manager.

Local advisory groups, such as LEPC's, would operate in the individual districts to coordinate local response with other community emergency response resources within the communities, such as volunteer fire departments, EMS's, etc. LEPC's would provide a policy-making body when local guidance is needed.

Five major sections of the cooperative would operate in both spill and non-spill periods. A command staff would assist the director in administrative, government coordination, and public information activities. An operational staff would prepare for and implement response operations in the field for a wide range of spill scenarios in various geographical locations.

The operational support/logistics section would handle a wide range of activities to enable the operations section to perform effectively in the field. This section would also manage the program for support vessels on contract with the ACCC, and provide support for the response activities of SERVS, CISPRI or member companies, as requested.

The operations support/financial section will manage all income and expenses, and handle all accounting/bookkeeping functions for the organization.

The technical response section would be responsible for strategic and tactical planning under the NIIMS Incident Command System (ICS), the training and technology development programs, and development of the Operations Response Plan.

A response core of full time employees would be supplemented by a trained local reserve in each community and by selected contractors, including response and support vessel owners and operators.

The heart of the ACCC is the local fishing fleets and other local vessels that proved to be indispensable during the *Exxon Valdez* spill response. Since that time, the efficacy of using fishing vessels for spill response has been recognized in other parts of the country. For instance, an organization called the Fisherman's Oil Response Team (FORT) is now in operation in the Clean Seas operating area near Santa Barbara, California. The Clean Sound (Washington) and Clean Coastal Waters (southern California) cooperatives have also budgeted funds for fishing vessel support programs.

Although the need to use local vessels became quickly apparent during the *Exxon Valdez* response, the methods for doing so were inefficient and inconsistent. In particular, the system of individual contracts between Exxon or its contractors and the vessel operators left much to be desired. Subsequent contracting procedures between Alyeska and vessel operators have solved some, but not all the problems.

Currently, individual contracts are negotiated between fishing vessel owners and both Alyeska and individual North Slope Crude Oil Tanker Fleet Operators for support services during an oil spill from a TAPS tanker. This is necessitated because Alyeska's contracts with fishing vessels are not transferrable to the Tanker Fleet Operators, who will be taking over from Alyeska 72 hours into the response. One can easily foresee the potential for disruption of spill response efforts due to contractual difficulties arising from this two-tiered process.

Creation of the ACCC would alleviate many of these problems by simplifying the process. As the contracting entity for the fishing and other vessels to be used on oil spills throughout Prince William Sound, lower Cook Inlet and the Kodiak areas, the ACCC can provide one-stop shopping for other responders in need of the service of local vessels. It is anticipated the ACCC would have in its reserve, most of the vessels appropriate for spill response activities, and an extensive data base of all pertinent specifications of those vessels. This will allow the ACCC to provide boats with the characteristics the responder needs without delay.

In carrying out the vessel contract service program the ACCC will follow several of these basic guidelines:

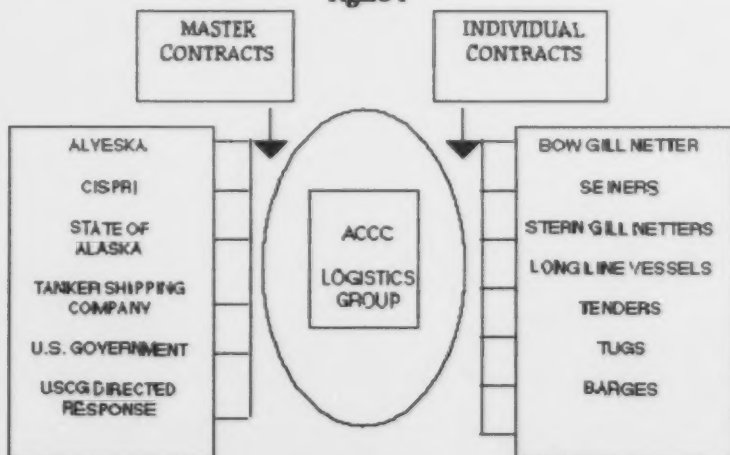
1. Compensation will be realistic in terms of costs incurred and activities foregone by participating in drills or spill response. For example, if a spill occurs during a short and valuable fishing season, the vessel operator is asked to forego this fishing opportunity, he/she should be reasonably compensated for the loss of this higher pay activity. Conversely, during other times, compensation would not include any such premiums.
2. During a spill response, vessels in the program will operate pursuant to NIIMS-ICS command structure. Industry's concern that vessel operators contracted for services will carry out their

services under the designated command structure will be addressed by a contract provision obligating vessel operators to do so.

3. Vessels provided under the program to a spill response would be instructed to remain on spill duties until relieved or replaced by a suitably equipped vessel and a properly briefed crew in order to provide assurance to the responder that vessel owners will not come and go as they please.
4. Participation in the program will be based on criteria including vessel specifications, crew qualifications, and past performance. All geographic areas will be represented in the program. The use of such criteria is intended to provide the highest level of service possible, while eliminating the potential for geographic or other favoritism or other unfair practices.
5. The ACCC would expect its members and other responders to route all requests for local vessel support services through the ACCC so long as the cooperative has the ability to supply the vessels needed.

An illustration of how the vessel contracting program would work is shown below.

Figure 1



V. EQUIPMENT AND OPERATING FORMAT OF THE ACCC

A capital budget for the ACCC was developed from a separate study that focused on selecting oil spill equipment specifically for use with fishing vessels and other local resources. The four main objectives of the equipment selected were to provide shoreline protection, nearshore

removal, support for limited shoreline cleanup operations and response to a product spill.

The equipment was to be distributed among one or more major bases along with secondary bases and isolated equipment depots. Key elements of the equipment base were:

- (1) Dedicated vessels for first strike response to product spills, initial shoreline protection activities and training activities.
- (2) Skimmers selected based on size and hydraulic requirements such that they can be used by many vessels in the Alaskan fishing fleet.
- (3) Small mini-barges configured as storage barges or for multiple purposes, which could be towed by vessels in the Alaskan fishing fleet - particularly seiners.
- (4) Boom of various sizes as appropriate for the ACCC's mission.
- (5) Three large storage barges to receive the oil collected in the smaller barges.
- (6) Transfer pumping systems.
- (7) Shoreside vacuum trucks for harbor spills, transfer and cleaning activities.
- (8) Communications equipment.
- (9) Safety, laboratory and special training equipment.

These resources, coupled with the reserve vessel and manpower resources would permit the statewide mobilization of 30 task forces - each with skimming vessel, a vessel of opportunity or a barge mounted skimmer and two or more mini-barges.

These task forces would be configured in different ways for different spills, but on a large crude oil spill, the task forces would (1) initially deploy shoreline protection resources; (2) either remove oil deflected or pocketed by the nearshore protection or assist in the interception and removal of oil approaching the shoreline; (3) remove the oil entrapped in the coastal system; and (4) assist in supporting shoreline cleanup activities.

The cooperative would have a capital budget and operating budget comparable with major West Coast cooperatives with appropriate extrapolation to Alaskan prices. A permanent core staff of oil spill professionals would develop the equipment base, participate in contingency planning and table top oil spill drills, maintain the vessel support program and resumes, and carry out training activities.

VI. SUMMARY

The organizational structures and response equipment necessary to initiate the first strike against crude oil spills in Alaska are largely in place. There are, however, a number of overall oil spill problems perceived unresolved or only partially resolved by this network of industry cooperatives, including:

- The need for an implementation plan for shoreline protection and nearshore response.
- The need to equip and train local residents to respond to oil spills.
- The need to effectively organize, train and use the capabilities of the fishing fleet and other vessels.
- The need to effectively respond to product (non-crude) spills throughout the state.

The Alaska Coastal Communities Cooperative (ACCC) provides a comprehensive and realistic solution to the major gaps in spill response in Alaska.

It is important that these problems be resolved in some manner. Either through the expansion of the role and mission of SERVS in Prince William Sound, CISPRI in Cook Inlet, SEAPRO in southeast Alaska, Alaska Clean Seas or some other mechanism.

The Regional Citizens' Advisory Council has sponsored the study of the ACCC. In the draft report the ACCC was presented as serving a crude oil spill role in Prince William Sound and Cook Inlet, and non-crude spills throughout Alaska. In the final report the scope of the ACCC was emphasized as the PWS - RCAC geographic area of responsibility, that is for a spill in Prince William Sound and all areas the spill would impact. The ACCC concept is valid under either geographic setting. One may ask - will the ACCC be implemented? Only time will tell!

The key groups to implement the cooperative are the North Slope Crude Oil Tanker Operators, preferably with the State of Alaska. Support and participation by the communities, non-crude storage and transportation firms, and fishing enterprises could strengthen the concept and broaden its geographic scope. Its implementation could either be immediate or through some implementation corporation similar to the way the MSRC began as the PIRO Implementation Corporation.

Recent Shoreline Mapping Projects in British Columbia and Significance to Oil Spill Countermeasure Planning

by

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ABSTRACT

A number of detailed physical shore-zone mapping studies have recently been completed within British Columbia, and results from these studies indicate that greater than 50% of the shoreline is comprised of beaches, in contrast to previous estimates indicating that less than 20% is comprised of beaches. Detailed mapping projects within southern British Columbia indicate about 55-65% of the coast contains sediment shoreline whereas the southern Queen Charlotte Islands have beaches on approximately 52% of the shoreline. Extensive reconnaissance surveys in support of the Pacific Coast Oil Spill (PCOS) Proposal on northwestern Vancouver Island and on the northern mainland coast support these results.

The results have important oil spill planning implications, in that sediment or beach shorelines are regarded as having a higher oil retention and oil residence period than rock shorelines, particularly coarse sediment beaches. However, ground observations at a wide range of locations on the coast indicate that the immediate subsurface sediment on many of the beaches are either fine sands or other impermeable material which would limit oil penetration and retention; high wave exposure coasts tend to have a thin veneer of sediment over impermeable bedrock whereas low wave exposure coasts often have a thin veneer of gravel over sand. Highly permeable, pebble/cobble beaches, which proved to have high oil retention and to be difficult to clean at the *Exxon Valdez* spill, appear to be uncommon with a distribution that appears similar to that of Prince William Sound (<5% of the shoreline).

The results have important implications to marine oil spill planning in the province. First, beaches are more common than previously thought and are likely to pose a more complex cleanup problem than would rocky shores. Secondly, ground observations indicate that surface sediment texture is not necessarily a good index of permeability, hence oil penetration and retention; oil spill sensitivity models must take this factor into account when estimating potential oil residence times for gravel beaches.

INTRODUCTION

British Columbia has a coastline length in the order of 25,000 km in length, a large portion of which is heavily utilized for recreational activities. Given that the second largest industry in BC is tourism and that the third largest industry is fishing, there is a high level of public concern about the BC coast's sensitivity to marine oil spills. The relatively small *NESTUCCA* spill, about 5,500 bbl, caused sporadic oiling along much of the western Vancouver Island coast and generated a cleanup effort involving hundreds of workers over a three month period even though only about 250 bbl were recovered along the BC coast by the cleanup operation (Harding and Langford, 1991). Since the spill and cleanup program, the coastal sensitivity to oil spills has remained a significant public concern.

STATEMENT OF THE PROBLEM

There is a high public interest in the sensitivity of the BC coast to oil spills, and there are a number of industry/governmental initiatives focusing on this problem. As such, regional estimates of the coastal character, particularly as it relates to potential oil residence in the shore zone, provides an important planning tool.

This paper reviews the distribution of major coastal morphologies along the BC coast with special emphasis on factors relative to oil persistence in the shore zone.

REVIEW OF COASTAL MAPPING PROJECTS

A number of regional overviews related to coastal morphology have been conducted (see Owens, 1977; Clague and Bornhold, 1980; Owens and Harper, 1983; and Harper and Owens, 1983). Owens (1977) estimate the total BC coastline length is in the order of 25,000 km (see also Cooper et al, 1971). Clague and Bornhold (1980) provide a regional description of the coast and as part of their presentation at the Coastline of Canada Conference (1978 in Halifax) summarized the relative occurrence of major coastal types (Table I); these data were based on interpretation of regional-scale data and vertical photo interpretations.

Table I BC Coastal Character
(after Clague and Bornhold, 1980)

COASTAL TYPE	OCCURRENCE
Bedrock	83 %
Mixed (Bedrock & sediment)	8 %
Beach	6.5 %
Fjord Delta	1 %
Open Coast Delta	1 %
Mud Flats	0.5 %

Over the past decade a number of more detailed coastal mapping projects have been conducted in BC for a variety of purposes including oil spill contingency planning, coastal zone management and recreational planning. Interpretations have been made from oblique aerial video imagery and vertical air photos to produce coastal morphology maps at scales ranging from 1:10,000 to 1:40,000. The greater resolution of the coastal morphology maps and the use of a single, systematic mapping approach, the BC Ministry of Environment's shore-zone classification system, provides the basis for compiling a revised regional overview of BC coastal morphology.

Locations of detailed mapping are illustrated in Figure 1 and data for major coastal substrate types are summarized in Table II. Rock coasts includes sediment-free rock cliffs, ramps and platforms; rock + sediment includes rock cliffs, ramps and cliffs with beaches; sediment coasts include beaches, sandflats and mudflats and deltas. Scatter in the data are a reflection of regional variations in coastal morphology. However, there is a consistent trend with respect to the distribution of sediment shorelines: **in all cases, the combination of rock +**

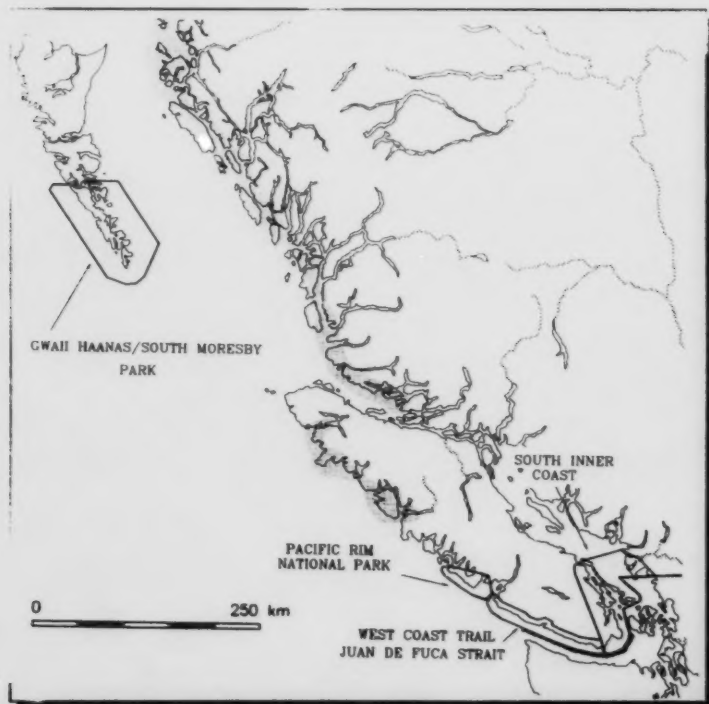


Figure 1 Location of coastal mapping projects. Shading indicates areas covered by the 1991 reconnaissance survey.

Table II Occurrence of Major Coastal Substrates

LOCATION	SOURCE	ROCK	ROCK + SEDIMENT	SEDIMENT
West Coast Trail	Harper, 1980	44 %	32 %	23 %
Strait of Juan de Fuca	Owens, 1980	44 %	7 %	49 %
Pacific Rim National Park	Harper & Sawyer, 1983	38 %	32 %	31 %
South Inner Coast	Howes et al, 1992	32 %	25 %	43 %
Gwaii Haanas/ South Moresby National Park Reserve	Harper et al, 1992	48 %	27 %	25 %

sediment and sediment shorelines account for more than 50% of the shoreline length. The occurrence of sediment along more than 50% of the BC coast represents a significant departure from previous estimates (Table I). In terms of estimating the potential for oil residence in the shore zone or for contingency planning, the data suggest an increased level of complexity.

These coastal mapping projects also provide some insight into the texture of the sediment on the shorelines, although the data are more difficult to compare than are the substrate data. The occurrence of sediment texture, summarized in terms of (a) gravel (pebble, cobble, boulder), (b) sand & gravel and (c) sand, are presented in Table III. The studies of the West Coast Trail, Juan de Fuca Strait and Pacific Rim Park use hard-copy, tabular databases which did not permit discrimination between gravel and sand & gravel beaches. However, the South Inner Coast and Gwaii Haanas projects clearly showed the occurrence of gravel, sand & gravel, and sand beaches.

In that the gravel (pebble/cobble/boulder) beaches represent the most permeable beaches and are similar to those beaches which retained the most oil after the *EXXON VALDEZ* spill, they represent a special concern in terms of both oil retention and in terms of cleanup.

Table III Occurrence of Sediment Texture on Beaches

LOCATION	SOURCE	GRAVEL	SAND + GRAVEL	SAND
West Coast Trail	Harper, 1980	?	5%	17%
Strait of Juan de Fuca	Owens, 1980	?	29%	6%
Pacific Rim National Park	Harper & Sawyer, 1983	?	~26%	~14%
South Inner Coast	Howes et al, 1992	15%	28%	12%
Owahi Haanua/ South Moresby National Park Reserve	Harper et al, 1992	24%	20%	8%

1991 COASTAL RECONNAISSANCE

During 1991, two of the authors (JRH,DFD) conducted an extensive coastal reconnaissance of northwestern Vancouver Island and the northern mainland coast of BC (see shaded area of Figure 1). Low altitude overflights were made using a fixed-wing aircraft and approximately 20 ground stations were visited.

Observations made during the overflight tend to confirm the results from these other studies both for coastal substrate (Table II) and for beach sediment type (Table III). That is: (1) beaches, occur on over 50% of the shoreline often in association with rock platforms or occurring as some pocket beaches and (2) the vast majority of these beaches are coarse sediment, either gravel beaches (pebble/cobble/boulder) or sand & gravel beaches.

SUBSURFACE SEDIMENT CHARACTER

During the reconnaissance survey about 20 ground stations were surveyed for subsurface sediment character; particularly consideration was given to the permeability of the beach sediments. The ground surveys were exclusively concentrated on "coarse sediment" beaches; that is, gravel or gravel and sand beaches.

A surprising result of the surveys and the subsurface sampling was that a high proportion of the beaches had a relatively low permeability. In the case of gravel or sand & gravel beaches, gravel was usually concentrated on the surface as a gravel lag one to two grains thick while the subsurface was predominantly sand. This sediment profile was typical of many of the "gravel" beaches in moderate to low wave exposure shoreline (wave fetches less than 50 km). Sufficient wave energy exists to remove surface sands, leaving a gravel lag, but there is not sufficient energy to remove subsurface sand or fines. As such these beaches appear "coarse" but because of relatively low permeability of the subsurface sediments, they are unlikely to be significant reservoirs for subsurface oil (Hayes et al, 1991).

Many of the exposed coast beaches (wave fetches > 100 km) also have a high proportion of gravel shorelines, although these beaches tend to be coarse with dominant cobble/boulder surficial sediment. Our ground surveys also indicated that many of these beaches had a relatively impermeable subsurface. Many of the exposed beaches that we visited had a boulder/cobble veneer over bedrock; the sediment layer was typically one to two clasts thick. Subsurface water tables were high due to the impermeable subsurface bedrock. On these beaches, the wave energy levels are sufficiently high to remove all sands and fines and even most pebbles. The result is a relatively thin veneer of cobble/boulder sediment over bedrock.

IMPLICATIONS FOR OIL SPILL PLANNING

These recently completed mapping projects provide a new perspective as to the occurrence of beaches along the BC coast. Most of the coastal regions of BC have beaches along more than 50% of the coast (Table I). The higher resolution mapping also indicates that the majority of these beaches are classified as "coarse" sediment; that is, either gravel (pebble/cobble/boulder) or sand & gravel.

The relatively high proportion of beaches, particularly coarse sediment beaches, has important implications to oil spill planning. In that coarse sediment beaches proved to be one of the most difficult shoreline types to clean during the *EXXON VALDEZ* spill, their high frequency of occurrence represents a significant concern in terms of estimating sensitivity of the coast and in developing cleanup strategies.

Our preliminary observations about the permeability of "coarse" beach sediments are also relevant to spill planning. Even though a high proportion of the BC coast is rimmed by gravel or sand & gravel beaches, many of these beaches are relatively impermeable due to low permeability subsurface sediments. In the case of low to moderate wave exposure beaches, the subsurface is predominantly sand. High exposure coasts frequently have cobble/boulder beaches, but only a thin veneer over bedrock. The impermeable nature of the subsurface would likely limit oil penetration and facilitate natural cleaning.

An important implication of these results are that surface sediment texture may not be a good indicator of permeability of the beaches. In the case of the low to moderate wave exposure gravel or sand & gravel beaches, the pebble/cobble appearance is generally a surface feature only. High exposure cobble/boulder beaches, which retained the most oil at the *EXXON VALDEZ* spill, often had an impermeable bedrock in the immediate subsurface and therefore a much reduced permeability. As such, subsurface sampling programs that document the subsurface sediment texture and permeability would significantly improve the confidence in potential oil residence estimates.

CONCLUSIONS

1. Recent, systematic coastal mapping results from several different regions indicate that beaches occur along more than 50% of the coastline in BC, often in association with rock platforms, ramps and cliffs.
2. Gravel (pebble/cobble/boulder) and sand & gravel are the most common sediment textures of the beaches; sand beaches comprise less than 10% of the coast in most areas.
3. Preliminary ground observations indicate that many "coarse" sediment beaches are relatively impermeable due to (a) fine subsurface sediment on moderate to low wave exposure beaches and (b) impermeable bedrock on many of the exposed beaches. Surficial sediment texture may not necessarily be a good indicator of beach permeability.

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THE USCG/ENVIRONMENT CANADA/ASTM
STANDARDS DEVELOPMENT PROGRAM

by

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BACKGROUND

Environment Canada's Emergencies Engineering Division (EED) has been charged, as a result of the Public Review Panel on Tanker Safety and Marine Emergency Response report, with increased R&D in marine oil spills. This activity will, of necessity, include development of standards and guidelines for the testing and/or usage of oil spill cleanup equipment.

The United States Coast Guard (USCG) has been charged with implementing the provisions of the Oil Pollution Act of 1990 (OPA-90) as it pertains to marine transportation vessels and facilities. Among the provisions are requirements for vessel and facility owners and operators to develop comprehensive response plans that specifically match response resources to spill removal requirements. Meeting the response plan provisions of OPA-90 requires common standards for testing, selecting and assigning resources to anticipated response needs and objectively evaluating response plans for adequacy.

In August 1991, the USCG OPA-90 staff wrote to ASTM concerning the possible use of the latter's standards development procedures as a mechanism for the required standards development. ASTM responded that this was a possibility and that 24 standards already existed. A meeting was convened in Washington, D.C. on 9 September at which it was decided that the two groups would work together and that the OPA-90 staff would meet with interested members of ASTM F-20 on Friday 14 October, in La Jolla, California at the end of the regularly scheduled F-20 meeting. It was decided during the course of that meeting to establish Task Groups under F-20 Sub-committees and that standards development could logically proceed in 11 areas. These were:

Barriers
 Skimmers
 Treating Agents
 Pumps
 Beach Clean-up
 Sorbents
 Bioremediation
 In-situ Burning
 Temporary Storage Devices
 Communications
 Remote Sensing

In order to accelerate the process of standards development without violating established ASTM procedures, it was decided that contractors would be hired to assist the F-20 sub-committees and task groups where such assistance was desired. USCG OPA-90 and Environment Canada, Emergencies Engineering Division would fund the services of the contractors. This would be done without subverting the normal ASTM process.

ASTM STANDARDS DEVELOPMENT PROCEDURES

ASTM is an organization whose committees are comprised of producers, users and persons having a general interest in a certain area. The committees, which cover specific areas, such as oil and hazardous material spills operate by consensus. Development of a standard normally proceeds as follows:

- A sub-committee will decide that standards development is required in a certain area and will either establish a task group for this task or carry out the work in the sub-committee.
- The task group or sub-committee will hold meetings to discuss the standards development.
- One member will volunteer to write the first draft standard(s) and circulate to the other members.
- The draft will be discussed at the next meeting and revisions will be suggested.
- After several iterations, the new or revised standard(s) will be ready for Sub-committee ballot.
- After any substantive negative comments or votes have been dealt with, the standard will be sent for full committee ballot.
- After any substantive negative comments or votes have been dealt with, the standard will be sent for Society ballot.
- Once a successful society ballot has been obtained, the standard is reviewed by ASTM staff then published.

The period from initiation of the process to society ballot may take from three to ten or more years.

PROGRESS TO DATE

During discussions between OPA-90 and Emergencies Engineering Division personnel, it was decided that an early start should be made and that the initial emphasis should be on containment and recovery. That would mean finding a contractor as soon as possible to address the areas of barriers, skimmers, sorbents, pumps and storage devices. A Request for Proposal sent to 4 Canadian and 4 U.S. contractors led to a contract being let to S.L. Ross Environmental Limited of Ottawa, Ontario.

A meeting of members of the ASTM Task Groups and the contractual staff was held on 15 January at USCG Headquarters. The contractors were charged with synthesizing the results of the meetings, commencing the development of standards where progress warranted, and having some written documentation to the Working Groups prior to the scheduled February F-20 meeting.

The ASTM F-20 meeting was held in Corpus Christi, Texas on 18-21 February, 1992. Meetings were held, albeit in some cases small meetings, in all 11 areas. Various degrees of progress were made. It was decided by the sub-committees involved that contractors were not required in areas other than those for which they had already been hired. In the latter case, it was decided to retain the same contractors at least through the October, 1992 meeting. An interim meeting was scheduled in conjunction with the Arctic and Marine Oilspills Program Seminar in Edmonton, Alberta on 9-10 June, 1992. All of the 11 groups except sorbents, communications, treating agents and beach clean-up are scheduled to meet.

METHODOLOGY

It is expected that the standards development process will follow a tiered approach with more general guidelines on systems and specific equipment usage and selection criteria being supported by test protocols for equipment. As earlier stated, some standards already exist. Others are in development or exist in other areas and can be modified. The first new and revised standards are expected to have ASTM approval within 24 months with the process continuing for 5 years.

The tiered approach starts with the realization that there are only three methods currently available for the treatment of oil spills. These are:

- Mechanical Containment and Recovery
- Chemical Treatment
- In-situ Burning

For each of these methods, a systems approach must be

taken. It is not sufficient to select one piece of equipment without regard for the others with which it will be required to operate. The physical environment is also important and may drive the system chosen. This approach is explained in the following example for selection of a mechanical containment and recovery system.

In order to select a system for mechanical containment and recovery, it is important to consider:

- a. the wind, wave, current and air and water temperatures likely to be encountered;
- b. the type and volume of oil or petroleum product moved into and out of the area;
- c. the way in which the properties of the spilled substance will change with time once it is on the water: and,
- d. the distance to the shoreline.

These parameters will then determine the optimum equipment mix in order to attempt to recover the product in the time available, hopefully before it hits the beach.

EXPECTED RESULTS

In the case of barriers, the standards existing are for definitions, membrane materials, tension members and the connector. The last named is an example of a very specific standard which can be used in the selection of a product. There are currently no ASTM test protocols in this area but a USMMS/EC/USCG group has established one such for the Ohmsett tank. This protocol is specific to off-shore equipment but the Task Group may be able to use it as a basis for more generic test protocols. General guidelines for equipment selection based on the product carried and the climatic conditions expected to be encountered in the area will have to be developed. A standard practice for describing environmental conditions relevant to spill cleanup exists but may require updating.

There are several ASTM standards in existence for skimmers. These are several years old and may require updating. Test protocols for the Ohmsett facility also exist but these rely heavily on the ASTM standards. General guidelines for equipment selection are also required in this area. A document outlining the expected capacities and limitations of the different generic types of skimmers would also be of use and will probably be developed.

Dispersants are currently the only widely used type of treating agent. ASTM has a complete family of guidelines

for the use of these products in fresh and saline environments. The sub-committee concerned are currently working on standards for airborne nozzles used in dispersant application. If effective treating agents other than dispersants, such as gelling agents or solidifiers, are developed guidelines will be required for these as well.

There are currently no ASTM standards for the use of pumps in marine oil spill cleanup. In fact, the only ASTM standards for pumps are very specific test protocols. Given the wide usage of pumps in oil spill cleanup and vessel unloading, standards specific to this area will be required. The Working Group considering this area is, however, dynamic and these should be produced relatively quickly.

Beach Clean-up is an area for which no standards currently exist. It is also an area where guidelines and standards will be difficult since it tends to be very subjective. The level of cleanliness which is achievable or practical following a spill of light oil near a major U.S. city may be completely different from that for a spill of heavy crude or fuel oil in the Arctic. Development of standards in this area will, therefore, be a long process.

ASTM F-20 has had standards for the testing of absorbents and adsorbents for six years. They are, unfortunately only infrequently used with most parties relying on the protocols developed and published by Environment Canada since 1979. In 1989, that group commenced a rework of their test protocols, incorporating the best parts of those from ASTM and Environment Canada. This work has been carried out in cooperation with ASTM F-20 and the Canadian General Standards Board (CGSB). A new protocol, for sorbents for marine oil spills, was largely accepted by all parties in February, 1992. It is currently being used by Environment Canada in a sorbent test program. Any difficulties with the protocol will be worked out by October of this year. The new standard should then be ready for ASTM Sub-committee ballot in February, 1993.

The U.S. EPA has been working in the area of bioremediation for several years and has a draft standard in this area. ASTM Sub-committee F20-24 has been active in the area for two years and has access to the EPA's work. As a result, a draft ASTM standard is in preparation. If the current rate of progress is maintained, the first ASTM bioremediation standard should be ready for sub-committee ballot within 18 months.

ASTM F-20 has several members with experience in in-situ burning either as an experiment or during the Exxon Valdez incident. The group planning the North American large scale test burn usually meets in conjunction with the ASTM F-20 meeting. As a result, although this is a new area for F-20, standards development should be a relatively

rapid process.

MSRC and USCG are currently both embarking on test programs for temporary storage devices. Both groups are represented on ASTM F-20. The development of standards in this area should, therefore, be a relatively simple process. As was the case for sorbents, the standards developed should be reflect experience.

Communications is a new area for ASTM. It is also considered to be an important area in oil spill cleanup. Several members of the committee have the experience in working with communications during spills. The development of new standards should progress well under their direction.

Some of the members of F-20 have over 15 years experience in remote sensing of marine oil spills. As such, development of ASTM standards should proceed smoothly. In this area, guidelines for the use of remote sensing during spills will probably be the first product.

CONCLUSIONS

In summary, the ASTM Committee F-20 and the US Coast Guard have embarked on an ambitious program of standards development in the area of marine oil spills. This process will be complex with several levels of standards being produced. A large number of people will be involved. It is, however, expected that the process will be fruitful and lead to standards useful to the regulator, the producer and the regulated agencies.

**Task Force on Oil Spill Preparedness:
Offshore Implementation Progress**

by

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Abstract

Industry members of the Canadian Petroleum Association (CPA) and the Independent Petroleum Association of Canada (IPAC) undertook a review of spill preparedness and response capabilities in 1989. In November, the report "Oil Spill Preparedness in the Upstream Petroleum Industry" summarized the then current state of readiness. It focused on oil spills resulting from exploration and producing activities in Canada. The report recommended expenditures in research and development, equipment acquisition and training to prevent and control offshore and onshore oil spills more effectively.

The release of the November 1990 report, "Implementation Plan - Task Force on Oil Spill Preparedness" (TFOSP) provided the impetus for a 5 year plan to improve this state-of-preparedness. The plan outlined the mechanisms for implementing the 45 recommendations developed by TFOSP. It also recommended how to incorporate them into the daily business activities of the Canadian Petroleum Association member-companies. It identified the appropriate groups within industry to carry out the implementation of each recommendation. It also indicated the government interfaces, the schedule for implementation and an estimate of the cost for putting each recommendation into place. It also recommended a vigorous monitoring program to follow and report on the status of implementation for these recommendations.

Based upon the recommendations of the TFOSP Implementation report, workplans were developed, specific work projects identified and a budget approved for 1991 programs.

The first year of implementation of the recommendations has now been completed and work plans have been developed for continuation in 1992.

Background

In 1989, the Canadian Petroleum Association (CPA) and the Independent Petroleum Association of Canada (IPAC) collaborated on the Task Force on Oil Spill Preparedness (TFOSP). Industry initiated this task force because of concerns in both associations on their abilities to respond to major oil spills.

In November of that year the associations released a report titled **"Oil Spill Preparedness in the Upstream Petroleum Industry."** This study assessed the Canadian upstream petroleum industry's readiness for dealing with oil spills resulting from exploration and producing activities. The report found that the petroleum industry's spill preparedness response compared favourably with the best found anywhere in the world. It also made forty - five recommendations for improvement. These recommendations applied to both onshore and offshore activities of the associations and had an estimated cost of \$13 to \$15 million over a five year period. CPA and IPAC endorsed the recommendations in the report, and the directive given to member companies to implement the recommendations of the task force.

In early 1990 an implementation committee was established to develop a plan for implementing the recommendations made by the task force. This joint CPA/IPAC committee was charged with developing implementation procedures, identifying responsible agencies and government interfaces, and estimating costs and timing schedules. It produced a report in November of 1990 titled **"Task Force on Oil Spill Preparedness - Implementation Plan."** This report presented a compilation of the findings of the committee. It also gave specific advice on implementation of each of the TFOSP recommendations over the next five years. Since that report was released, the industry associations, oil spill cooperatives and individual petroleum companies, have been working to implement the TFOSP recommendations.

The Plan identified the appropriate groups within industry to carry out the implementation of each recommendation. It also identified the government interfaces, the schedule for implementation and an indication of the cost for putting each recommendation into place. It also recommended that a vigorous monitoring program be developed to follow and report on the status of implementation for these recommendations.

The following sections describe the progress made in implementing the TFOSP offshore recommendations in the first year of implementation (1991).

1991 Workplans

One of major recommendations of the TFOSP Implementation report was to form a new industry research association. Modelled on the experience of COOSRA (Canadian Offshore Oil Spill Research Association), it would implement the offshore Research and Development recommendations. COOSRA was formed in 1980 by industry to fund major oil spill research. As a result in November of 1990 the CPA Frontier Oil Spill Committee was formally established to deal with the TFOSP recommendations.

TFOSP further recommended that to effectively implement the various recommendations, a full-time manager be hired to coordinate and direct the implementation of the TFOSP programs. A manager was seconded from Gulf Canada in March, 1991 to take on the position of Frontier Oil Spill Manager.

Utilizing the efforts of individuals on the Frontier Oil Spill Committee, workplans were developed for each of the 20 recommendations for the offshore. The key recommendations were grouped into three major project areas:

- o Planning and Prevention
- o Research and Development
- o Equipment and Training

Industry spent approximately \$4.2 million in 1991 expenditures in the three areas. One of the key philosophies agreed upon by the Frontier Oil Spill Committee and the Manager was to obtain the best value work for the monies expended. This included searching out existing work programs and investigating participation in jointly funded projects with other organizations and agencies. Meetings were held with key funding groups in Environment Canada, Canadian Coast Guard, PROSCARAC, Alaska Clean Seas Co-operative and Marine Spill Response Corporation.

Following is a summary of the major achievements in each of the three areas.

1) Planning and Prevention

• Communication Systems Review

The objective of this project was to review the present status of capabilities to provide short term and long term communications support to a major spill response. A contract was let and completed in early 1992 analyzing communication resources and requirements for the offshore Arctic, offshore Nova Scotia and offshore Newfoundland. The report provided guidelines on recommended equipment and systems to provide support for major responses in all three regions.

• Incident Command System

Incident Command has been utilized by several major companies to deal effectively with a major spill response. In developing better response methods, the CPA hosted several Incident Command System (ICS) seminars in 1991 in Calgary. The objectives were 1) to introduce the concept to emergency response planners and 2) to obtain candid viewpoints on the advantages and disadvantages from people knowledgeable with ICS. Representatives from BP America and Alaska Clean Seas presented overviews of their experience with ICS, and how it worked within their organizations. A similar seminar was held in Vancouver in early 1992. The next steps involve feedback on the interest level from member companies and how CPA can further assist with these efforts.

• Spill Expertise Database

The CPA, working with PROSCARAC, the onshore umbrella cooperative, developed an on-line computerized personnel database of oil spill expertise. The listings can be accessed by CPA member companies and provide contact information for specific spill expertise. The listings cover CPA member companies and consulting oil spill specialists. It is intended to expand this to cover a wider array of experience and include government support specialists.

Other workplan areas under Planning and Prevention included Government/Industry consultation and Contingency Planning guidelines.

2) Research and Development

• Viscous/Waxy Oil Handling

One of the difficulties identified in East Coast spill response was the problem of transfer and handling of viscous, waxy oils. This study provided a preliminary, engineering assessment of various concepts for reduction in viscosity of weathered crude oils and emulsions. It also looked at the reduction in skin friction drag associated with pumping the recovered fluids. The objective was to identify concepts and systems that, alone or in combination with others, could significantly reduce pumping problems associated with recovery at sea of Grand Bank's crude oils and their emulsions. The study identified promising methods including: the use of emulsification breakers at the skimmer, shearing recovered oil and stored oil, the warming of recovered oil and the injection of pour point depressants. The ultimate goal of this project is to provide the design guidelines to optimize the recovery and transfer of viscous, waxy oils.

• Oil Spill Model for the Grand Banks

This recommendation from TFOSP indicated a need to develop an oil spill trajectory model for application to the Grand Banks, offshore Newfoundland. After assessment by the Frontier Oil Spill Committee, CPA joined the consortium of companies and organizations working with Applied Science Associates to develop a generic model for application offshore. The other funding agencies include Environment Canada, Exxon, Mobil U.S.A., Chevron U.S.A. and the U.S. Army Corps of Engineers. This two year program will provide the most up-to-date oil spill trajectory model for application offshore. This co-operative approach is fostering the use of a common model by industry and regulators. An operational version of the model should be completed by end of this year - 1992.

• Oil in Ice Cleanup

CPA through TFOSP undertook several initiatives in this project area. During 1991, TFOSP 1) supported an observer for the field investigation of the LORI Ice Skimmer; 2) conducted a state of the art review on oil in ice recovery methods and 3) conducted a field test of the Foxtail skimmer system.

The state of the art review project undertook: 1) to review technical reports and papers on the recovery of oil in ice published since the mid-1970's, including R&D, concepts, evaluations and spill incident

data; 2) to catalogue the compiled data according to methodology and 3) to project the performance potential of each concept in the context of actual cleanup. The assessment considered work conducted in Canada, the United States, Norway, Sweden, the United Kingdom and USSR. A series of conclusions and a listing of the more promising concepts was included. Joining CPA in providing funding support for the program was Alaska Clean Seas, Environment Canada, and Marine Spill Response Corporation.

The Foxtail testing program was a joint effort of CPA, Alaska Clean Seas, Canadian Coast Guard, Marine Spill Response Corporation, Environment Canada and Cook Inlet Spill Prevention and Response Inc. The performance of the skimmer was assessed in a lined pit with North Slope Crude oil and diesel. The tests took place at the Tesoro Refinery near Kenai, Alaska in early December, 1991. The specific objectives of the program were: 1) to measure skimmer performance in North Slope Crude oil and diesel and record associated machine settings, oil characteristics and ambient conditions; 2) to identify operational deficiencies and suggest modifications that have the potential to improve skimming and 3) to make recommendations for rigging details and procedures required for sea trials in conditions of broken ice. The conclusions indicated that the Foxtail skimmer comprised an excellent oil recovery concept with good potential and versatility for many oil-in-ice applications. Recommendations on improving performance were made and additions and modifications suggested to optimize deployment and operation.

Other research and development areas being investigated includes: Remote Sensing, Oilspill Chemicals, Shoreline Cleanup, and Effects Monitoring.

3) Equipment and Training

- **Spill Response Equipment Inventory**

One of the key recommendations designed to facilitate improvements in spill response was establishing a standardized inventory system for use by all Canadian operators. CPA is working closely with PROSCARAC to produce such a format. The program is using the Spill Expertise database format and provides equipment listings for the major offshore co-ops in Canada and the PROSCARAC co-ops in western Canada. As with the Spill Expertise database, information is available on-line through modem access.

- Response Equipment Improvements

Significant capability improvements were made by both major offshore co-ops in Canada in 1990 and 1991.

The Beaufort Sea Co-op conducted a major review of capability in 1989, following its involvement in the response to the Exxon Valdez spill. Based upon recommendations to the owners, the Co-op completed major additions and modifications to equipment in 1990 with the acquisition of two high-capacity skimmers, several transfer pumps, four helitorch ignition systems, 450 m of fireboom and 1000 m of rugged offshore boom. The Spill Response Barge was completely renovated, and the new systems installed. Trials were undertaken in Tuktoyaktuk with the new systems.

The Eastcoast Spill Response Inc. co-op in Newfoundland completed a major equipment acquisition program in 1991. Two major offshore skimming systems were acquired and delivered in 1990 and 1991. These acquisitions increased ESRI's ability to recover free floating, high viscosity oil in a higher sea state. The offshore recovery ability was also significantly improved with purchase of an open ocean boom system 1991. A trawl containment pocket was later added to concentrate oil thickness for recovery. Training sessions with both were conducted in the fall of 1991. ESRI also built two chemical delivery systems in 1991 for delivering emulsion breaking chemical to the skimmer heads.

The hardware acquisitions and improvements by the Beaufort Sea Oil Spill Cooperative and East Coast Spill Response Inc. totalled approximately \$3.8 million. No further equipment improvements are planned for 1992.

Other projects underway in this area include a review of Successful Training Strategies, investigating a Database of Training and developing Training Standards.

Summary

Overall the TFOSP implementation plan is proceeding on schedule and on budget. The co-operation shown to date with other funding agencies and organizations provides confirmation of the desire to share resources and expertise within Canada and North America. The 1992 program will continue with work in the three key areas of Planning and Prevention, Research and Development and Training.

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An Incident Command System in Practice and Reality¹

by

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The best technical methods for responding to emergencies do not guarantee a successful response operation. Effective application of technology requires a management system that can quickly organize and focus people from many disparate organizations. Arguably the most renowned such system is the Incident Command System (ICS) that was created twenty years ago to deal with large wild-land fires in California. ICS has since been fine tuned into the national model for dealing with all types and magnitudes of emergencies in the United States.

In September 1990, Canadian and United States Coast Guard On Scene Coordinators agreed to apply ICS to CANUSLAK '90, a field and command post exercise of the Joint Canada/United States Marine Pollution Contingency Plan. Three days later, many of the Michigan-based exercise participants were reunited on the occasion of the largest Great Lakes maritime calamity in over a decade -- the spectacular explosion, burning, and sinking of the T/V *Jupiter* in Michigan's Saginaw River. This paper first describes the basic organizational problems and options for forming a response organization. It then summarizes how ICS was used to quickly meld dozens of organizations and hundreds of people into a single, coordinated response organization at both CANUSLAK and the *Jupiter* casualty. Finally, it outlines the major components of ICS, recommends how ICS can be made to work, and lists sources of additional information.

Multi-agency Response Characteristics

Multi-agency Response Organization Problems.

Many Need to be Present. Major pollution incidents, especially when associated with casualties or natural disasters, draw large numbers of invited and uninvited organizations such as those shown in Figure 1. (AETC, p. 21) Each usually has an obligation to attend the casualty and be part of the response team. Each invariably has something to offer at some stage. In the early phases of an operation, medical, fire fighting, damage control, and safety/security resources may be most desperately needed. Later phases require investigation, cleanup, and restoration of damaged resources. The person(s) leading operations must not dismiss

¹ Opinions in this paper belong to the author and are not necessarily shared by the U. S. Coast Guard or other noted organizations or persons. The paper is oriented toward pollution and emergency response management in the United States.

organizations that may be required later, nor should they be permitted to freelance, i.e., operate independently with little or no coordination with, or accountability to, other elements of the response organization.

Figure 1. Types of organizations participating in responses to major casualties and disasters.



Coordination Problems. Everyone is eager to help; most will join a multi-agency response team if asked, and if they have a stake in the success or failure of the team's efforts. However, aspects of organizational behavior and human nature must be overcome. Many are blind to concerns and issues outside of their normal purview. Bureaucratic organizations may have difficulty operating in the crisis environment. Strong personalities can cause egos to clash. Fear of losing control leads to power struggles. Pervasive political concerns muddy reality. Some organizations lack confidence in others and thus will duplicate tasks. It is a recipe for organizational chaos — on top of the chaos inherent in the disaster.

Accountability Problems. Elements of the loosely bound multi-agency response organization may lack clear accountability and authority for their actions. (AETC, p. 1) Those actions may influence the extent of property loss, environmental damage, diminished public and political goodwill, and loss of livelihood, health, and perhaps lives. The news media, public, and politicians will search for scapegoats. Harmed parties will file lawsuits and allege negligence. Professional careers are tarnished or ruined. Poorly thought-out actions, perhaps by freelancing organizations and individuals weakly connected to the response organization, are difficult to defend.

From the *status quo* to ICS. Organizations responding to an incident fall into, or are molded into, one or a combination of the following types of response organizations:

- Type A Autonomous Organizations, Minimal Coordination.* Each organization is narrowly focused on what is within its purview. Interaction with other organizations may be limited to what is necessary to reduce conflict. Different mandates and procedures, lack of confidence or trust in other organizations, and poor communication foster redundant efforts. Organizations may purposely remain independent, or they may be left out by other agencies that are working together as Type B or C response organizations. Type A may sometimes be appropriate and is a natural initial phase of a rapidly growing response organization; however, it is the antithesis of a coordinated multi-organizational response effort. Type A is not further addressed.
- Type B Autonomous Organizations, Affirmative Coordination.* There are affirmative efforts to coordinate activities. Resources are shared, but are closely controlled by the "owner" organization. Multi-agency/organization teams are formed to address different activities; however, individual members have primary allegiance to their respective agencies/organizations. Many pollution contingency plans foster a Type B response organization.
- Type C Organizations Formed into Single Response Organization.* Representatives of participating organizations are formed into one response organization. Positions in the organization are based more upon individual expertise rather than agency affiliation. Concerns and unique procedures of individual organizations are accommodated; however, the response organization works for one leader and is focused on one action plan. ICS fosters a Type C response organization.

From Chesapeake Bay to San Francisco Bay, and Curacao to Valdez, I've worked to create the Type B response organizations fostered by the United States model – the National Oil and Hazardous Substance Pollution Contingency Plan. It repeatedly stresses a coordinated multi-agency

response. (U.S. Nat'l Oil...) Although the plan calls for a federal On Scene Coordinator (OSC) to coordinate the deployment of needed resources, it does not prohibit a firmer Type C response organization. The Type C organization is called for by hazardous material response health and safety regulations stating "...the senior emergency response official responding to an emergency shall become the individual in charge of a site-specific Incident Command System (ICS)." (U.S. Occupational..., §1910.120(q)(3)(i)) Although the Joint Canada/United States Plan uses the term On Scene Coordinator/Commander, the details of the plan imply a Type B "coordination" arrangement. (Canada...) Pollution contingency plans are generally strong in their alerting procedures, designation of a lead coordinator, and identification of jurisdiction, resources, strategies, and tactics. Pollution plans are generally not as strong with respect to the following characteristics, which happen to be ICS design criteria: (USFEMA, pp. ix & x)

- *Flexibility as to the jurisdiction and agency providing for scenarios such as: single jurisdiction with single agency involvement, single jurisdiction with multi-agency involvement, and multi-jurisdiction with multi-agency involvement.* Pollution plans generally address response organization leadership relative to the pollution incident, but are less specific or ignore situations where other organizations have major jurisdictional purview. This is especially critical when pollution is on a par with or overshadowed by issues such as fire fighting, flooding, civil disturbance, etc.
- *Organizational structure being readily adaptable to any emergency or incident.* Pollution contingency plans are typically narrow in focus. They don't account for the possibility of pollution being a minor issue compared to fire fighting or other issues that may be addressed by a different lead agency, using a different organizational structure. This leads to forming separate organizations to address separate issues of the same incident.
- *Application and acceptability to users throughout the country.* Each federal OSC responsible for maintaining pollution plans has leeway concerning the choice of organizational framework and many of the procedures to be employed. Responders must learn and accept those local methods and procedures, or attempt to fulfill their responsibilities without joining that organization.
- *Capability to expand in a logical manner from an initial attack.* Local pollution response plans often propose sample organizations for certain size incidents, but don't adequately address how to get there, or how to get to the organization required for a catastrophic incident.

- *Uniform elements in organization, terminology, and procedures in order to allow maximum application of qualifications and standards, and mobility/applicability from place to place.* Such elements are sufficiently unique to each organization and local pollution plan so that regional, national, or international participants will be hobbled until they learn of the local standards. Many organizational positions have no detailed description of responsibilities and position specific action checklists. The learning curve for someone newly appointed to a position in an activated response organization can't be eliminated, but should be reduced.
- *Implementation not disrupting other existing systems.* The single issue focus of the pollution plan's organization poses potential for disrupting other systems by not addressing how it fits with or within parallel, or larger, response organizations. For example, perhaps pollution response operations should not be independent of related flood relief operations, but rather should come under an overall command structure, and compete for and share resources with other operations such as building a levee, searching for survivors, and providing shelter and medical services.
- *Effective fulfillment of the above criteria with ability to keep costs low.* Factors that can help lower costs include economies of scale, common standards (applicable to any participating organization), and familiarity with a system gained through its broad application from the smallest to largest incidents. A system in which only one agency is comprehensively trained is inefficient if it applies to many agencies. The system is also inefficient if it is designed for the rare catastrophic incident, and requires inordinate overhead to maintain familiarity with that system.

Adopting ICS need not gut the pollution plan; ICS and a pollution plan can complement one another. The area pollution contingency plan for southeastern Michigan no longer directly addresses organizational and procedural aspects that are better addressed by ICS. (USCG MSOD, Oil...) The plan incorporates ICS by reference. ICS covers those operational procedures that are common across the full spectrum of emergencies and supporting organizations. ICS is one way to form many organizations into a single Type C response organization, a way to assign accountability and focus supporting organizations on a single set of collective objectives.

ICS in Practice – CANUSLAK '90

CANUSLAK Preparations. In August 1990, Coast Guard Marine Safety Office Detroit, and our Canadian and Michigan counterparts, prepared for a major command post and field exercise of the Joint Canada/United States Marine Pollution Contingency Plan. We knew that the "incident"

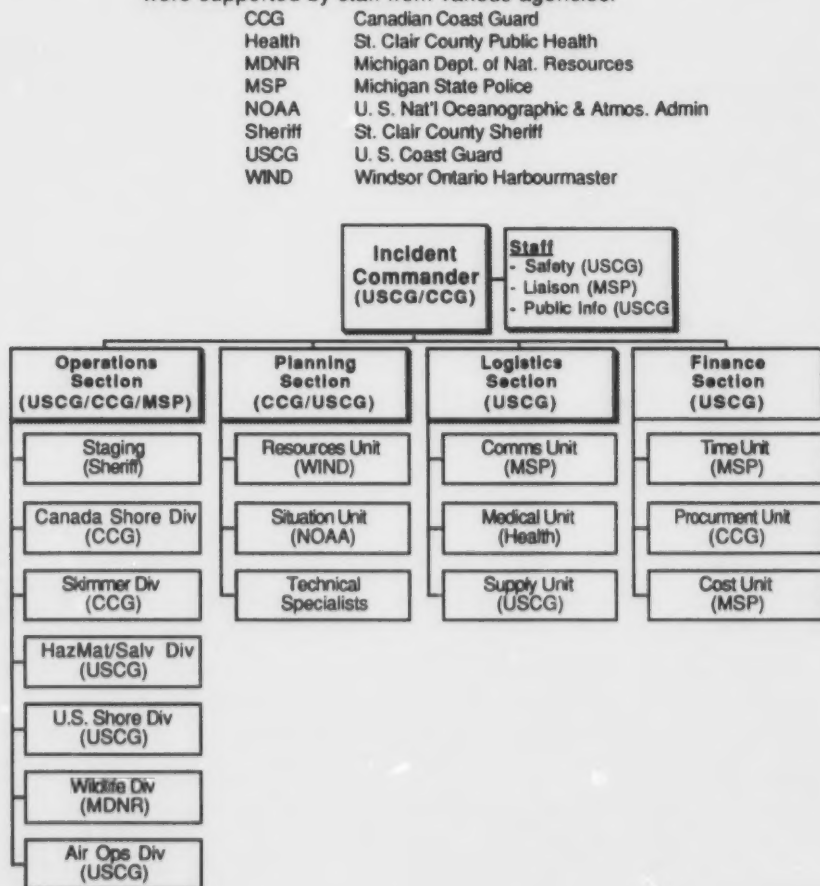
would occur in the St. Clair River (drains Lake Huron), on the United States side of the border; therefore, the U. S. Coast Guard and a Canadian Coast Guard would provide the OSC and deputy OSC, respectively. We would not learn details of the casualty, participating organizations, or how many participants to expect until the two day exercise began. My task was to integrate participants into our response organization as they arrived.

As previously noted, the organizational and procedural framework of the contingency plans lent themselves to forming a Type B response organization. A Type A situation would likely prevail during the chaotic initial stages of the operation. We would struggle to wrest control and establish the Type B organization typical of previous exercises of the Joint Plan. Canadian and United States forces traditionally had formed into separate organizations on either side of the border, coordinating efforts by telephone and radio at various levels of the respective organizations. Such an arrangement encouraged redundancy, confusion, break-downs in coordination, and inefficient allocation of resources. We looked into the suitability of ICS.

Applying ICS to CANUSLAK '90. We consulted with experts, studied reference materials, and gained confidence. We intended to fully apply ICS in all its refinement, well beyond the typical seat-of-the-pants, no paperwork ICS applications common to many fire fighting and emergency medical operations. We would issue the detailed ICS position descriptions and position checklists to those assigned to dozens of positions. We would use the ICS procedures, supported by ICS forms in page and wall chart size, and mark incident facilities with prepared ICS signs. (USNWCG Nat'l. Fire Equip...) An order for ICS materials was telefaxed to the U. S. Bureau of Land Management warehouse at the Boise Interagency Fire Center in Idaho. The order was shipped for overnight delivery with billing to follow -- just the kind of service required for emergency operations.

Although there are formal ICS courses, including specific courses on many of the dozens of ICS organizational positions, we concluded that the quality of ICS documentation would enable us to make ICS work without formally training participants. During the week before the exercise we planted the ICS seed with fewer than a dozen people from several agencies. Each was assigned a senior management position of the planned ICS response organization. Each was given an overview article on ICS, the position descriptions for themselves and for subordinate positions, and written responsibilities, procedures, and forms dealing with their part of the organization. We knew nothing of the scenario or how the response organization would finally look. Each manager was told he would be assigned people from an unknown pool of exercise participants who would arrive during the first morning of the exercise. Each would be responsible for melding participants, most of whom never heard of ICS, into his part of the ICS organization as the exercise progressed.

Figure 2. The CANUSLAK response organization is shown with the agency affiliation of those filling lead/deputy positions. Most positions were supported by staff from various agencies.



CANUSLAK began with the expected chaos; hundreds of field response workers and agency representatives arrived at field work sites and the command post – every person trying to learn what was happening, where to go, and what to do. Field operations were brought under control during the morning as communications nets were established, and as supervisors reached hundreds of response workers at shoreline and afloat work sites and at staging areas. A hundred more representatives from all levels of government from both nations, and from commercial and private organizations, were assigned to ICS positions located in the command post. The ICS organization, as depicted in Figure 2, was generally based on

who was available and their area of expertise, not government affiliation. For example, the Canadian Planning Section Chief was assigned a deputy from the U. S. Coast Guard, and the Situation Unit Leader was the NOAA Scientific Support Coordinator. His team of scientists included members of the U. S. Army Corps of Engineers, and Michigan and Ontario natural resource and public health agencies. It was exciting to watch the synergy of individuals from many different organizations working side by side and focused on one action plan.

The comprehensive ICS procedures for establishing organizational relationships, and controlling personnel, facilities, equipment, and communications, quickly made ICS credible to the participants. Procedures didn't have to be invented. Procedures unique to one agency were not imposed on other agencies. The response organization quickly gained a level of maturity well beyond its short life. There was no inclination to revert to the more autonomous Type A or B response organizations, there was little freelancing.

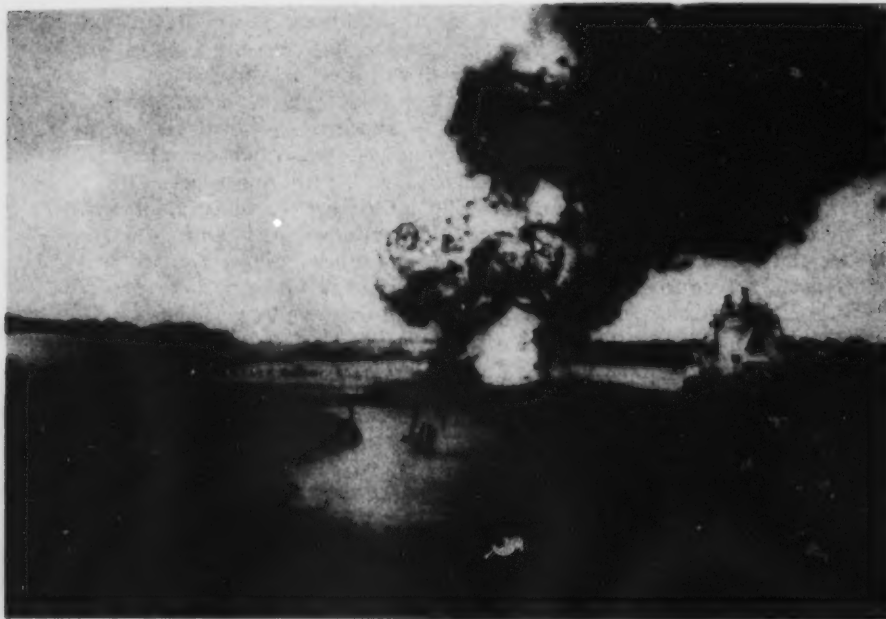
CANUSLAK Critique. At the post exercise critique participants acclaimed how ICS unified and provided a common ground for so many people from a myriad of organizations; the organization enabled individuals to know the big picture of their assigned areas and efficiently allocate resources. Participants in previous CANUSLAKs stated that ICS made this the best organized, most effective exercise in their experience.

ICS in Reality -- T/V *Jupiter* Casualty

The Casualty. Several days after CANUSLAK, on September 16th, the calm of a Sunday morning on Michigan's Saginaw River was broken as the gasoline laden *Tank Vessel (T/V) Jupiter* was wracked by explosions. (USCG MSOD, *T/V Jupiter...*, p. 1) Many of CANUSLAK's Michigan-based participants joined hundreds of other response personnel from three dozen of organizations. The fire was out of control until regional and national resources were marshaled for an assault that extinguished it on the 17th. The fire reignited several hours later, and was extinguished again during the afternoon of the 18th. The fire and explosions destroyed all internal tank bulkheads, blew off tank tops (main deck), and weakened the vessel so that it sagged at the mid-section and was in danger of breaking in half. The *Jupiter* settled with it's bow aground with plenty of freeboard, the mid-section awash, and the aft end afloat and obstructing the channel. In the next weeks remaining pollutants were removed, the hulk was strengthened, and a system was constructed for treating millions of gallons of contaminated water that would need to be pumped out. Just over a month after the casualty occurred the *Jupiter* was raised, moved to a scrap yard, and the last debris removed from the channel.

The incident was a major inland pollution incident, however, the pollution aspects of the case were overshadowed by many equal or more

Figure 3. Explosion of the gasoline laden *T/V Jupiter*; the *M/V Buffalo* had just passed.



important issues. Other issues included: heroic rescues of most crewmen; the spectacular fire requiring unique fire fighting platforms and equipment; extraordinary operations to move and secure the ship (it was tethered by only one of its six mooring lines and in danger of sinking in the channel); a complex salvage operation with a novel means to treat contaminated water; and the use of ICS to ease the creation and working of a particularly complex response organization.

The Bangor Township Fire Chief was Incident Commander (IC) while the fire was burning. The Coast Guard OSC was the IC from September 19th, when the fire was extinguished, until October 21st, when the channel was finally cleared. Using ICS, the Fire Chief IC organized the first responding organizations (his department, supporting fire departments, emergency medical services, and the local Coast Guard station which had just rescued many of the crewmen). He was quickly overwhelmed by hundreds of response personnel from over three dozen participating organizations (including the Governor of Michigan). He couldn't readily integrate them into his organization.

During the first day a State Police Fire Marshal and the Coast Guard OSC led efforts to identify key agency representatives and forge responding organizations into a single ICS response organization. For example, the Bay City Fire Department had staged their command post and fire fighting apparatus in their city, remote from the IC's command post. The most ominous threats were the ship breaking in half and releasing a large amount of burning gasoline, or the parting of the single remaining mooring line securing the ship against a stiff wind. Either event would broaden the scope of the casualty. An OSC representative arranged for the Bay City Fire Chief to survey the area from the air, and then went to his command post to help formulate a defensive plan to protect three vulnerable facilities on the Bay City side of the river -- a sulfur plant, an oil terminal, and a railroad bridge. Within minutes fire fighting apparatus and fire fighters from Bay City and other localities were moved to protect those critical areas. The Bay City Fire Chief became a key part of the IC's organization rather than working independently.

The lead representative from each of the principal operational organizations represented his organization at planning meetings. For example, the Coast Guard OSC led and represented many Coast Guard personnel, boats, ships, and aircraft on hand to support operations. Similarly, the Governor's declaration of a disaster enabled the State Police Emergency Management Division to lead and coordinate state agencies. The shipping company president represented company resources and companies that they contracted for cleanup, salvage, etc. Agency representatives were of all of high enough rank to commit resources and declare agency policy. Although lead agency representatives had veto authority on how their resources were deployed, for practical purposes, all resources supported the IC's action plan. A consensus of the lead agency representatives supported most major decisions. This contributed to the high level of confidence placed in the response organization by the Governor of Michigan, the media, and the public, even during the first day when the fire burned out of control as response resources were being marshalled.

What ICS Did. As was the case at CANUSLAK, ICS combined many organizations into one team with a single IC. The easily applied organizational framework contributed to the rapid maturity of the response organization, and exceptional levels of teamwork. There was no attempt to apply the detailed ICS procedures, forms, or to create as many of the positions as was done for CANUSLAK. In hindsight, more formal procedures and position assignments may have been helpful; however, the informal approach worked well. Preparations for CANUSLAK had cultivated many good relationships, and control of operations was eased by operations covering a relatively small geographic area.

What the Incident Command System Is

ICS is Traditional Good Management. The precepts of ICS are not new; they are time honored principles of organization, planning, goal setting, and record keeping found to varying degrees in many management regimes, including pollution contingency plans. What is different is the degree to which ICS has been developed as an emergency management system, and the extent of its credibility and acceptance among the emergency response communities in the United States.

ICS Roots. ICS has its roots in a series of fires that swept large wild-land areas of southern California in 1970. The organizational difficulties of these large multi-agency responses included ineffective communications, lack of accountability, and lack of a well defined command structure. (USFEMA, p. 1-3) Municipal, county, state, and federal authorities formed an organization known as FIRESCOPE (Firefighting Resources of California Organized for Potential Emergencies). FIRESCOPE designed the original ICS for managing fire fighting.

ICS has since been greatly refined. It has evolved into the model "all-risk" system, i.e., for fires, floods, earthquakes, hurricanes, tornados, tidal waves, riots, hazardous material/oil spills, and other natural and manmade incidents. The National Fire Academy (NFA), Boise Interagency Fire Center (BIFC), and numerous state and local emergency management organizations have adopted ICS. Tens of thousands of emergency managers have been trained in the system. It is also recommended by National Fire Protection Association (NFPA) Standard 1405 (Land-Based Fire Fighters Who Respond to Marine Vessel Fires) which was developed at the request of, and in cooperation with, the U.S. Coast Guard.

There are other incident management systems. Some are encrusted in the traditions of their organizations, some are heavily oriented toward special purposes, and others are variations of ICS. However, FEMA, NFA, state emergency service agencies, and other prominent organizations are in a strong position to influence national standards. They have made ICS the most popular and credible system -- the closest to a national system of emergency management in the United States.

ICS Components. The eight basic components of ICS are:

- I. Common Terminology
- II. Modular Organization
- III. Integrated Communications
- IV. Unified Command Structure
- V. Consolidated Action Plan
- VI. Manageable Span of Control
- VII. Designated Incident Facilities
- VIII. Comprehensive Resource Management

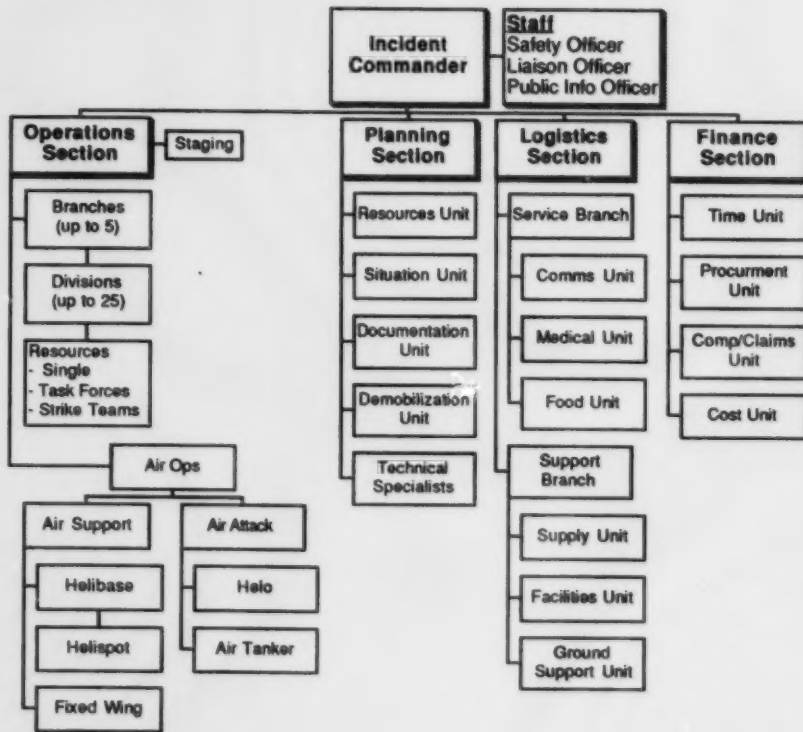
I. Common Terminology. A common nomenclature is the unifying language of the multi-organization response. Categories of terms and some sample terms are:

Organizational	position names	<i>medical unit leader</i>
	organizational components	<i>planning section</i>
	organizational procedures	<i>incident action plan</i>
Resources	personnel	<i>hand crew</i>
	equipment	<i>dozer, tanker</i>
	grouped resources	<i>task force, strike team</i>
Facilities	operating locations	<i>staging area, helibase</i>

Most ICS terms are generic to any response organization. Terms such as *water tender* are specific to the fire fighting roots of ICS. *Tractor plow*, *aerial torch*, and *air tanker* were coined with fire fighting in mind, however, they are just as suitable to defining equipment used to remove oil from a beach, burn oil *in situ*, or apply oil dispersants from a fixed-wing aircraft. The ICS glossary needs additional terminology related to pollution and other types of emergency responses; however, existing terms should not be unilaterally replaced with terms that will confuse those already well-grounded in ICS. For example, some might advocate changing certain ICS terms to terms commonly used by that organization (for example, change *Incident Commander* to *On Scene Coordinator*). This may make ICS more palatable to those wedded to a particular field, but would confuse those who occasionally work in that field using non-standard terminology. Changes of ICS terminology should be through a standards committee that would ultimately change ICS references and training curricula.

II. Modular Organization. The ICS organization starts with designating the Incident Commander, usually the senior member of the first response unit. There may be one or more changes of IC as the response organization changes, or as individuals from agencies with more jurisdictional responsibilities arrive. The IC has full authority and responsibility. Responsibilities initially include all applicable items listed in the dozens of potential ICS position descriptions. The IC often can independently manage operations, planning, logistics, and finance for minor incidents. As warranted by the incident complexity and size, and numbers of response resources, the organization develops from the top-down. Responsibility and authority in areas that can no longer be handled by the IC are transferred as the IC appoints others to section chief and command staff officer positions. In turn, section chiefs will assign individuals to positions required within their sections. Many of those activated positions may require staff support. A complex incident could require activating all four sections, and many of the units of each section shown in Figure 4.

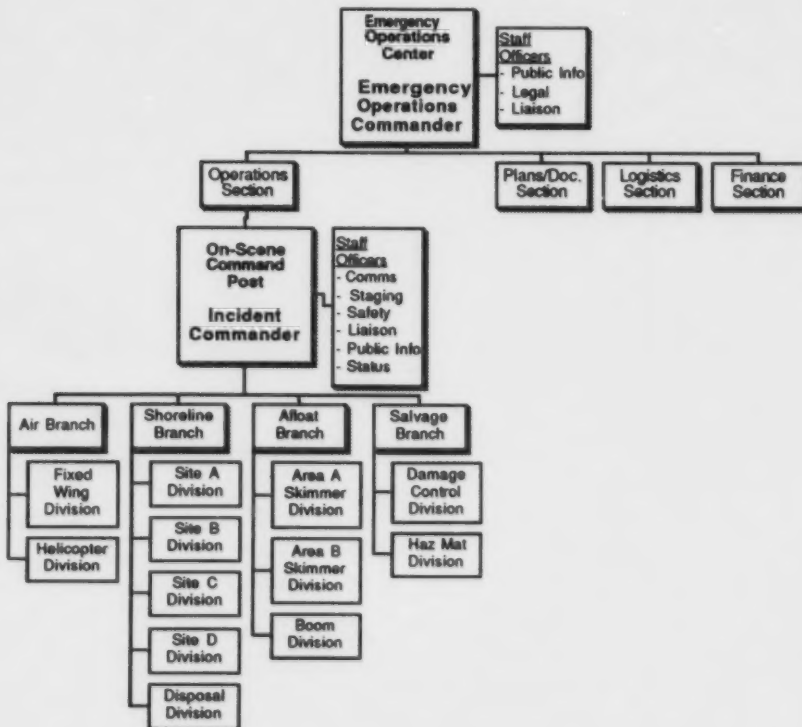
Figure 4. ICS response organization showing many of the over 50 positions for which position descriptions, responsibilities, and procedures are described in the referenced position manuals.



Leaders at each level of the organization have distinctive organizational titles:

Incident Command	—	Incident Commander
Command Staff	—	Officer
Section	—	Section Chief
Branch	—	Branch Director (optional level)
Division/Group	—	Division/Group Supervisor
Unit	—	Unit Leader

Figure 5. Response organization with an Emergency Operations Center.



A catastrophic incident might require the direct involvement of political leadership or very senior management. ICS provides for an area command authority in an Emergency Operations Center (EOC). Figure 5 shows staff officers and support sections at a remote EOC with the IC running operations at the command post. Another variation might have a leaner EOC (for example, without the sections) supervising two or more ICs. This would be suited to response operations with distinctly different operating areas, requiring each IC to have a fully developed organization.

III. Integrated Communications. Communications protocol calls for the use of "plain language" -- no radio codes or agency specific acronyms. On hand communications equipment is integrated with the organization's needs, needed equipment is obtained (telephone, telefax, public address, microwave, satellite links, message systems, and radios). If the incident

warrants a communications unit, that unit leader creates and implements a formal communications plan using guidelines in position description and communications manuals. A large organization may require many radio nets, i.e., command, support, ground to aircraft, aircraft to aircraft, and several tactical operations nets. A national radio cache is available.

IV. Unified Command Structure. Major casualties and disasters have no regard for jurisdictional boundaries. Even when there is one IC from one agency, all agencies having jurisdiction are able to contribute to the creation of incident objectives, strategies, planning criteria, integrated tactical operations, and optimizing resources. If response organizations cannot agree upon one IC, ICS provides for a unified command (UC) structure. Representatives of those agencies with major jurisdiction can form a UC, jointly assuming IC responsibilities. With consideration of other participating organization concerns, the UC develops common objectives and strategies to guide the development of a single action plan. A single individual, the operations section chief (normally from the agency with the most jurisdictional concerns) implements the action plan.

A UC could have been established at the *Jupiter* response, however, a single IC is usually appropriate even if many organizations have jurisdiction or responsibility. In the *Jupiter* case, agency leaders agreed that IC would reside with the local fire chief when the vessel was burning, and with the Coast Guard at other times.

V. Consolidated Action Plan. Every response organization needs an action plan to stay on track toward objectives; it can be supplemented by information that all must know (such as radio frequencies, emergency medical protocol, and position assignments). For small incidents it is sufficient that the IC convey an informal action plan to an immediately available response organization. Written plans are desirable when resources from several agencies are committed, when several jurisdictions are involved, or when the duration of operations requires shifts of personnel. The action plan should cover all tactical and support activities for the period covered by the plan. The action plan may include sheets describing incident objectives, incident briefing, radio communications plan, organization and division assignment lists, medical plan, and the weather. This information is easily organized and presented using standard ICS forms. A table describes who originates and receives each type of form. (USNWCG ICS Forms, p. 4)

VI. Manageable Span of Control. A supervisor's span of control ranges from three to seven immediate subordinates; five is the usual guide. Exceptions might be made for leadership of more easily monitored crews working in small areas — for example, one supervisor for a 20-person hand crew manually cleaning the shoreline. A manageable span of control increases accountability, adherence to the action plan, and reduces the freelancing that can cause injuries and loss of control.

VII. Designated Incident Facilities. Facilities are designated for an incident. Everyone trained in ICS knows the purpose of each facility and what position is responsible for that facility. Guidelines and procedures for operating the facility are in the the appropriate referenced ICS Position Manual. Facilities include:

A command post from which the IC or UC operates.

An emergency operations center remote from the incident to accommodate political and senior leadership, and their support functions.

A communications center at or near the command post.

An incident base for support activities such as equipment storage and servicing, food preparation, and berthing.

Staging areas for checking in and temporarily holding reporting resources pending prompt assignment.

A mobilization center located away from the area of operations for longer-term holding of available and out-of-service resources.

VIII. Comprehensive Resource Management. As noted under CANUSLAK preparations, an extensive inventory of materials is available to help organize and manage resources. Detailed procedures, ready-made signs, label tags, color-coded T-cards, and forms (some in poster size) can aid a myriad of tasks ranging from equipment inventory and checkout, to scheduling aircraft operations, to reallocating, demobilizing, or obtaining additional resources. The use of materials and procedures is well documented in the referenced position and forms manuals. A number of ICS position descriptions delineate procedures for tracking resources.

Resources are assigned a status condition of *Assigned, Available, or Out-of-Service*. They are deployed one of three ways:

- *Single resources* are individual pieces of equipment (with operators) such as skimmers, helicopters, or vacuum trucks. They may be assigned independently or as primary tactical units.
- *Task forces* are made from any combination of resources assembled for a specific mission. During the T/V Exxon Valdez removal operations, the groups of resources centered around a mother ship, and working as a unit in specific geographic areas, were properly called task forces.
- *Strike teams* are set numbers of resources of the same type, with an established number of operators and a leader. For example, a strike team of skimmers would work in concert under one leader. Strike

teams are made up of equipment, teams of manual laborers, or any resource that becomes more efficient tactically when working in multiples.

The use of task forces and strike teams reduces communications load and the difficulty in managing a large number of single resources.

Making ICS Work

Our applications of ICS were successful despite limited ICS experience. Training and experience enable an easy, seamless formation of an emergency response organization and its procedures.

Use it in Routine Operations. ICS does not have the problem of systems designed for rare contingencies such as catastrophic oil spills; narrowly focused systems and plans are taken off of the shelf, dusted off, and applied by a less than adequately practiced or prepared response organization. In contrast, ICS can and should be part of routine operations. One organization even applies it to administrative projects ranging from creating training plans to preparing for the annual summer picnic. Routine use eases such projects while making ICS second nature and readily applied to infrequent larger incidents.

Training. Standard ICS course modules are widely available in the United States, especially in the fire fighter community. For example, my experience has included ICS seminars at a national fire fighter conference, a two day Ohio Fire Academy workshop tailored to a Coast Guard audience, and teaching an ICS overview session at the Michigan Hazardous Materials Conference. The National Fire Academy teaches overview courses; the Boise Interagency Fire Center (BIFC) in Idaho offers many courses focused on specific ICS positions.

The fire fighting roots of ICS, and the fact that fire fighters are the primary first line emergency responders, is apparent in the examples and some of the terminology used in much ICS material. This may be disconcerting to non fire fighters, however, the trainee experienced in fields such as law enforcement, natural resource management, industrial safety, and pollution control, should find the ICS materials and curriculum easily transferable to that experience. The BIFC is developing ICS courses without the fire fighting orientation. As ICS instruction is tailored to other agencies, the types of examples and terminology will readily expand, however, this can be taken to an extreme. For example, a consultant recently trained Alaska's Cook Inlet Spill Prevention & Response Inc., in their copyrighted Oil Spill Emergency Response Management System (OSERMS®). (HARTEC) As a liberally customized iteration of ICS, OSERMS® has good points, but it dilutes or eliminates many of the previously described design criteria and components of ICS.

Planning & Exercising with Response Counterparts. Routine operations seldom require much coordination with other organizations. It is risky or, at best, awkward to practice ICS when joining forces with other agencies to deal with an emergency. That is neither the time to learn the system used by another agency providing the IC, or to compel other organizations to accept ICS or your own system. Joint planning sessions, workshops, and exercises hone procedures and cultivate good working relations. They offer the opportunity for a relatively painless introduction to ICS, or to any other new procedures and techniques.

Conclusion

Rarely are benefits of preparedness so obviously drawn as between the CANUSLAK '90 exercise and the *T/V Jupiter* casualty. The demonstrated smooth integration of numerous agencies and personnel was testament to the effectiveness of the Incident Command System. ICS compelled the creation of one organization, with well defined positions filled by capable parties from all participating response organizations, and working toward the objectives of a single action plan. ICS reduced the natural inclination of individuals to be blinded to concerns other than those of their own organization. Narrow issues, such as pollution control, were dealt with in the same arena as the myriad of other issues raised by the incidents.

There are other systems for incident management and more will be created; however, ICS is currently the benchmark with respect to depth, flexibility, refinement, and wide acceptance and credibility. If your review reveals a better alternative than ICS for your emergency management needs, adopt that alternative! It will be a very good system!!!

Acknowledgements

I gratefully acknowledge the support of the U. S. Coast Guard. My sincere appreciation goes to Captain Thomas Daley, Commanding Officer of Marine Safety Office Detroit, Inspector David Charney, Assistant Division Commander of the Michigan State Police Emergency Management Division, and Mr. Bernard Leonard, District Manager, Canadian Coast Guard Parry Sound District. On behalf of their organizations, they accepted the significantly risky venture of fully applying ICS to CANUSLAK '90. They recognized that a large contingent of participants would arrive with little or no familiarity with ICS. The successful outcome is testament to the commitment of all participants, as well as to the quality and refinements of ICS that allowed it to be used under less than ideal conditions. We should expect nothing less from whatever incident management system is employed to bring order out of chaos.

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PERFORMANCE OF THE SEASONDE HIGH-FREQUENCY RADAR SYSTEM FOR SURFACE CURRENT MEASUREMENTS

by

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ABSTRACT

Intercomparison of currents measured with the new SeaSonde with drifter data have shown the SeaSonde speeds to be unbiased with scatter characterized by a standard deviation of 10.3 cm/s. Mean absolute speed differences averaged 7.8 ± 6.7 cm/s not accounting for speed errors in the drifters of ± 4 cm/s. Trajectories calculated from the SeaSonde surface currents showed good agreement with the drifters, reproducing tidally induced loops and eddies in the flow. Separation scales of the predicted and measured trajectories were typically 7 ± 1.5 km after 36 h and 9 ± 2 km after 48 h. The SeaSonde currents were judged reliable using the drifters as ground truth, noting the differences in time averaging (none for the drifters and 1 h for SeaSonde) and the depth of flow sensed by each.

1.0 INTRODUCTION

In August of 1991, the new SeaSonde HF radar system (Hodgins, 1991) was deployed at the southern end of the Queen Charlotte Islands to monitor the strong tidal surface currents in that area over a 21-day period. This was the first wilderness deployment of the new system. Four days of near-surface drogued drifter data were also collected for comparison with the radar-measured currents. Some features of the deployment are discussed in this paper, together with the results of the intercomparison, using both Eulerian and Lagrangian methods.

Five Sea Rover drifting buoys were deployed in or near the radar coverage area between August 21 and 24, 1991. Each drifter was fitted with a 5-m long holey sock drogue and eight independent drift tracks were measured, ranging in duration from 17.5 to 48 h (Table 1). The time between position fixes was 30 minutes. The Sea Rover buoys use Loran C for positioning, which in Queen Charlotte Sound is believed to be accurate to no better than ± 50 m (pers. comm., W. Crawford, Institute of Ocean Sciences, 1992). The corresponding error in the velocity components is ± 4 cm/s.

Winds during this period were moderate, at 10 to 20 knots steady from the northwest, with brief periods of speeds of 5 to 10 knots.

Table 1: Sea Rover Drifter Deployment Times in Queen Charlotte Sound

Drogue Number	Start Date Time (dd/mm/yy) (GMT)	End Date Time (dd/mm/yy) GMT	Length (hours)
G30	21/08/91 17:00	22/08/91 22:00	29.0
H30	23/08/91 07:30	24/08/91 01:00	17.5
E31	21/08/91 18:30	23/08/91 18:30	48.0
H32	21/08/91 20:00	23/08/91 00:00	28.0
I32	23/08/91 07:00	24/08/91 02:00	19.0
I37	22/08/91 17:30	24/08/91 03:00	33.5
G38	21/08/91 20:30	23/08/91 01:30	29.0
H38	23/08/91 05:30	24/08/91 04:30	23.0

2.0 DEPLOYMENT AND MEASUREMENT PROPERTIES

The rugged, inaccessible terrain on the east coast of Khunghit Island provided only two possible sites at which to locate the radar units: Cape St. James (the weather station) and Lyman Point (a tiny island), located 16.8 km along the baseline as shown in Fig. 1. This is a comparatively short baseline separation (ideally the radars are separated by about 40 km) resulting in a total current coverage area occupying a small fraction of the dual-radar illumination region defined by the radar measurement range of 60 km.

Portability and low power demand were two of the design objectives for the new radar units. The photographs in Fig. 2 show the installation at Lyman Point. The RF hardware and data acquisition computer was housed in a two-man Hurrident, all powered off a single 2,500 W portable generator. The receive antenna was located about 40 m from the tent, separated from the transmit antenna by roughly 25 m. Both antennas were mounted on standard surveyor's tripods, and required only a small clear area exposed to the ocean. The set-up time for one radar unit was under two hours once the site had been prepared by clearing an area for the tent and generator.

HF radar principles for measuring surface currents are summarized in Hodgins (1991) and Hardy et al. (1989), and are described in detail in Lipa and Barrick (1983). In the new SeaSondes an FMCW (frequency-modulated continuous wave) signal format is used, centered at a frequency of 12.5 MHz. Range resolution is achieved by sweeping the frequency linearly over a 50 kHz band yielding a range resolution of 2.557 km. There are 31 range cells, giving a total theoretical range of just over 79 km. The voltages from each receive antenna are Fourier transformed using a 512-point FFT. The spectral resolution is 0.00390612 Hz, which for the radar frequency of 12.5 MHz is equivalent to a Doppler velocity resolution of approximately 3.3 cm/s. A running spectral average is then formed from 14 consecutive sample spectra, and the averaged Doppler spectra in each range ring were

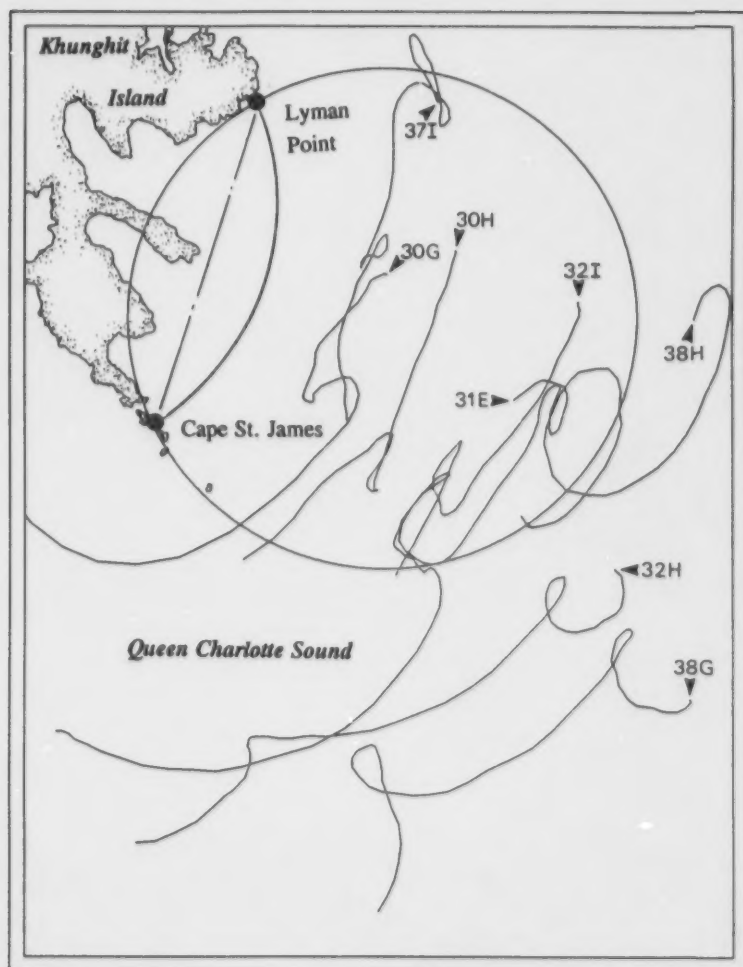


Figure 1 Map of Queen Charlotte Sound and Khunghit Island showing the radar locations and the eight drifter trajectories. The circle describes the two-site coverage area for the baseline joining Cape St. James and Lyman Point.



Figure 2 Antenna positioning at Lyman Point. Tx denotes the transmit antenna and Rx denotes the receive antenna. The receive antenna is shown in the lower photograph. All RF hardware and data acquisition computer was housed in a two-man tent in the pine trees above the Tx antenna, powered from a single portable generator.

used for the extraction of radial velocities. Thus, the radial velocities represent a 1-h time average of the actual flow field.

3.0 SURFACE CURRENT CALCULATION

Radial velocities at each radar were extracted from the sea-echo spectra using the least-squares method described by Lipa and Barrick (1983). The method statistically tests the single and dual-angle models for radial currents and selects the one having the best fit to the data. The DF procedure yields the azimuth angles as a function of radial velocity. This function must be inverted to give the radial velocity map, and is done on a regular grid of points in polar coordinates. The azimuthal increment used in the present analysis was 5° . This method of radial current extraction yields optimum estimates of the speed, v , and its standard deviation, δv , at each angle in the field of view.

Total current vectors were calculated by combining the radial data from each radar site on a 1 km by 1 km Cartesian grid (EW-NS orientation) within the coverage area. The coverage area was divided into area cells, and all radial velocities from both radars falling into a given cell were interpreted to give a total current velocity. The circular area cells have been centered on each Cartesian grid point and defined by a blending radius R_b . The total current speed and direction were found by least-squares fitting to the radial components following the algorithm described in Lipa and Barrick (1983). Two thresholds were imposed on each radial velocity, v , in the area cell: $\delta v \leq 10$ cm/s and $v \leq 200$ cm/s. If either threshold was exceeded, that radial velocity was excluded from the fitting procedure. An example of one pair of radial currents maps, and the corresponding total vector field is shown in Fig. 3.

The coverage area is defined by the triangulation angle γ , which is the angle between azimuths from each radar site, intersecting at a combining grid point. Leise (1984) has shown that velocity errors are a function of γ ; the minimum error is found at $\gamma = \pi/2$, and increases as γ tends to zero and 180° . Leise presents criteria defining the coverage area as a locus of points satisfying the geometrical error function with $\epsilon = 2$. These criteria have been used to define the coverage area shown in Fig. 1.

4.0 OPTIMUM BLENDING RADIUS

There is no objective criterion for selection of the blending radius R_b . It must be large enough to provide a sufficient number of radial components to define the total vector with confidence, but not so large that it smooths out real features of the current field. By assuming that the drifter data provide a true measure of the surface current, the hypothesis that an optimum blending radius value exists that minimizes the difference in measured current speeds, and hence gives the highest accuracy, was tested. Two statistics have been examined: the difference between SeaSonde and drifter

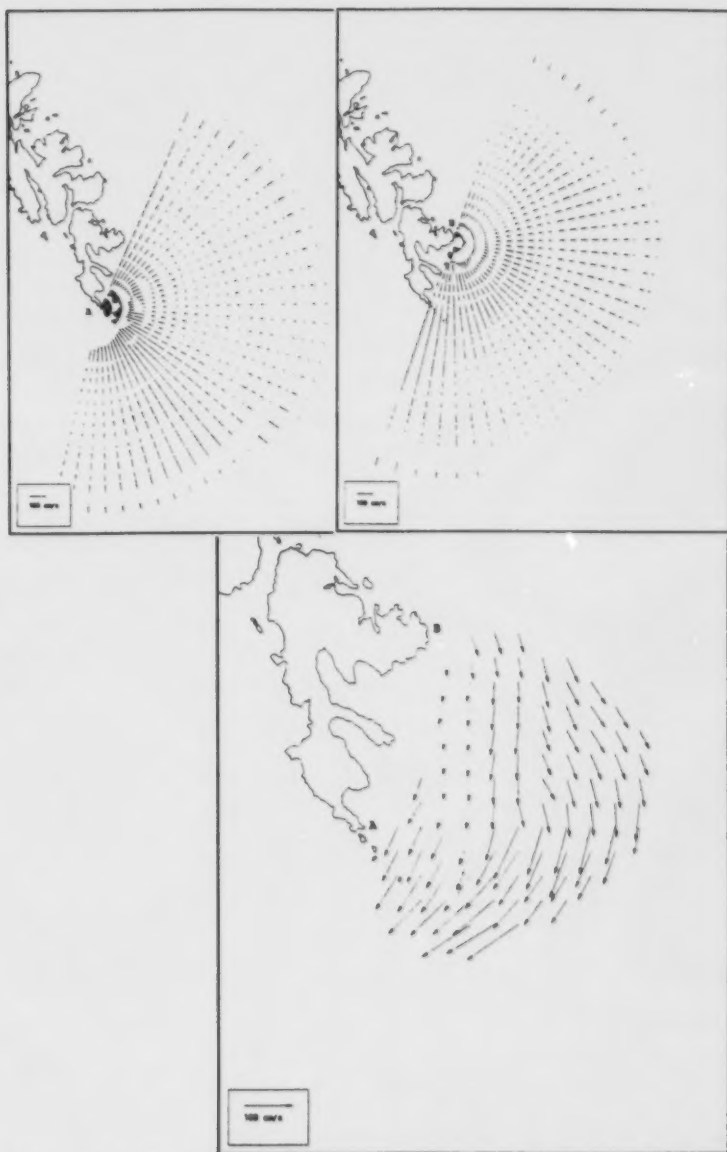


Figure 3 Examples of radial current components from Cape St. James and Lyman Point, and the combined total surface current map.

current speeds ($R_s - R_d$), which is a measure of bias, and the absolute difference in speed, $|R_s - R_d|$.

The tests were performed using two drifter trajectories centrally located in the coverage area. The mean value of each difference in speed has been calculated for averaging radii varying between 2 and 10 km. The drifter speed R_d has been calculated as the straight-line distance travelled between successive position fixes divided by 30.0 minutes. The SeaSonde speed R_s was calculated as an average along the space-time path defined by the drifter trajectory using the hourly radial current fields for interpolation.

Mean values for 104 observations of ($R_s - R_d$) and $|R_s - R_d|$ are shown in Fig. 4. The variation of $|R_s - R_d|$ exhibits distinct minimum at radii of 4.5 to 5.5 km, while the bias error has a zero-crossing at about 5.3 km. The bias has a second zero-crossing at 3.25 km; however, the coincidence of zero bias and a minimum in the absolute difference at about 5 km suggests that this is the optimum radius for blending the radial data.

4.0 COMPARISON OF SEASONDE AND DRIFTER CURRENTS

4.1 Eulerian Statistics

Radial Current Components. Radial current speeds (components oriented towards or away from each radar) are compared with the equivalent drifter component speeds for three trajectories (I37, H30, and H38) in Fig. 5. Two of the trajectories are centered in the coverage area, and one (H38) lies mainly outside the area. The radial current at each drifter position has been calculated from the SeaSonde data using a 4-point bilinear interpolation in range and bearing, weighted inversely by the variance of each radial speed. If one or more of the radials were missing, the comparison point was omitted. Generally, the data from each site plot on opposite sides of zero. The correlation of radial speeds is high for all drifters; however, the scatter is slightly greater at H38 than at closer ranges.

Surface Current Vectors. Surface currents components, combined with a radius $R_b = 5$ km, are compared with the drifter current vectors for tracks I37 and H30 in Fig. 6. These tracks were chosen for their central position in the coverage area. Speeds ranged from less than 5 cm/s to over 80 cm/s, and the SeaSonde shows a high correlation with the drifter data.

The average absolute difference in total current speed for these trajectories (104 observations) is 7.8 cm/s with a standard deviation of 6.7 cm/s. Assuming that about ± 4 cm/s of this difference is accounted for by the error in the drifter velocity, it appears that the radar and drifter differ by about an equivalent amount. The drifter speeds are calculated from punctual data, and thus do not provide an equivalent measure to the 1-h average of the SeaSonde. Moreover, the drifters integrate about 5 m of the surface shear, and differ slightly from the SeaSonde measurement. Thus, the additional

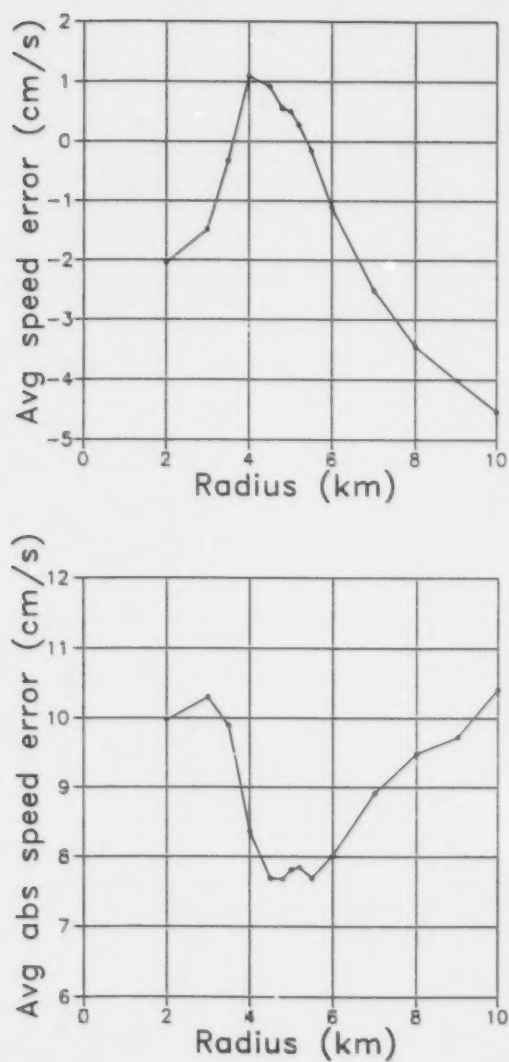


Figure 4 Average speed error (upper panel) and average absolute speed error (lower panel) versus blending radius R_b for drifters H30 and I37.

difference of ± 3 to ± 4 cm/s likely arises from the real difference between the surface current and the 5-m drogued drift current, and from error in the radar measurement.

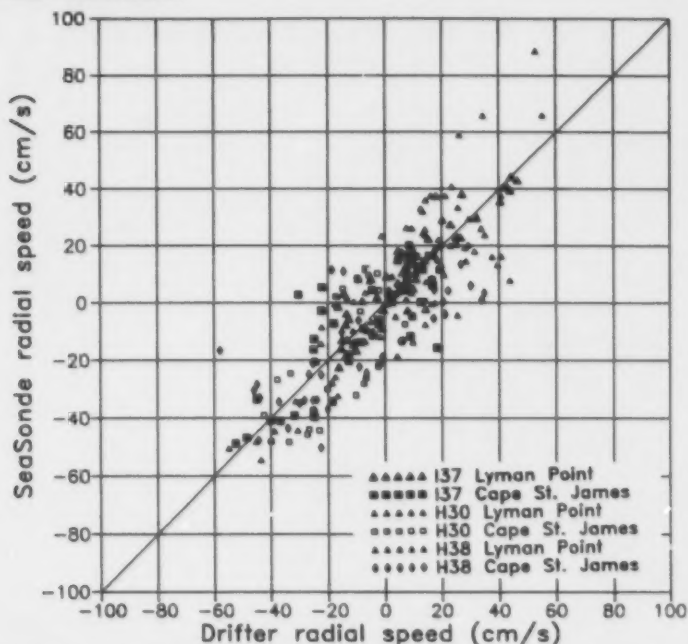


Fig. 5 Scatter diagram of SeaSonde versus drifter radial current speed.

4.2 Lagrangian Comparison

The currents measured with the radar have been used to calculate a set of trajectories initialized at the time and location of the beginning of the measured drift tracks. The predicted trajectories have been calculated from the relation

$$\mathbf{X}(t) = \int_0^t \mathbf{U}_s(\mathbf{x}, t) dt \quad (4.1)$$

where $\mathbf{X}$ is the position vector and $\mathbf{U}_s$ is the surface current vector derived from the SeaSonde radial currents with $R_0 = 5$ km. The integral in (4.1) was solved in a sequence of N discrete time steps with increment Δt such that N evenly divided the 30-minute time step of the drifter positions. N was varied between 1 ($\Delta t = 30$ min) to 15 ($\Delta t = 2$ min) and the separation distances were compared to determine if the predicted tracks were sensitive

to the integration time step. Predicted drift positions were calculated every 30 minutes, corresponding with the measured trajectories.

A two-step predictor-corrector procedure (indicated in the following equation by subscript 1), applied at each integration subinterval Δt , was used to integrate (4.1) for each 30 min time increment, i.e.

$$X(N\Delta t) = \sum_{n=0}^N \langle U_1 \rangle \cdot \Delta t + X(0\Delta t), \quad l=1,2 \quad (4.2)$$

where $\langle U_1 \rangle = (U^{n+1} + U^n)/2$, with $U^{n+1} = U^n$ for $l=1$.

Mean separation distances, defined by $(X_1 - X_0)$, and standard deviations, were calculated for four trajectories to test the sensitivity of position to the value for N . It was found (see Hodgins and Hardy, 1992) that no increase in accuracy was achieved with a space-time step of integration less than 30 min.

Representative comparisons of predicted and measured trajectories are shown in Fig. 6 and 7. The trajectories generally exhibit good agreement, where many of the tidally induced eddy-like features found in the drifter tracks are reproduced by the SeaSonde predictions. On balance, the total displacement of the SeaSonde tracks is slightly greater than the drifters, consistent with a stronger currents right at the sea surface than integrated over the drogue depth.

Separation $(X_1 - X_0)$ versus elapsed time is plotted in Fig. 8 for each of the six drift tracks. The longest trajectory, I37, was modelled well, with the separation distance increasing more-or-less steadily with time. After 33 h the separation was about 7 km. Except for drifter H38, the separation distance generally increased with time and was bounded above by 7 km about 15 to 20 h after release.

The mean separation and one standard deviation are plotted in Fig. 9 for elapsed times out to 15 h. This is the longest time for which meaningful averages could be obtained. These results show that the separation distance tends to increase steadily for about 6 h, after which it assumes a roughly constant value of about 3 to 4 km. This tendency to a constant separation was consistent with the observed behaviour of the tracks, four of which tended to converge between 5 and 15 h, while two others continue to diverge, with some small variations. The average works out to a roughly constant value.

5.0 CONCLUSIONS

The combining radius for processing radial current components from two radar units has been shown to have an optimum value within the centre of

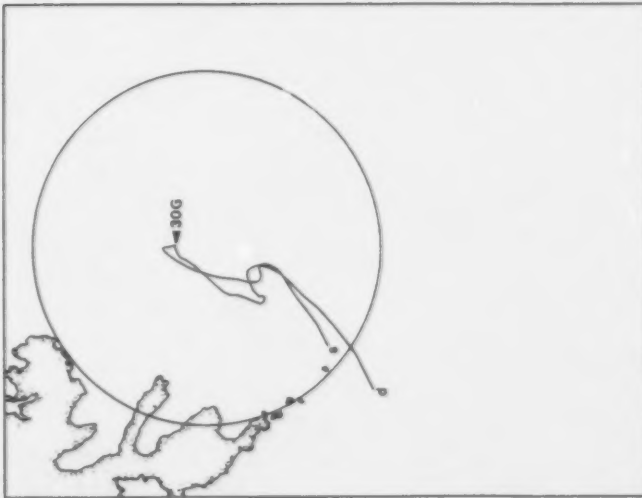


Figure 7 Comparison of predicted (s) and measured (d) drift track for trajectory G30.



Comparison of predicted (s) and measured (d) drift track for trajectory 137.

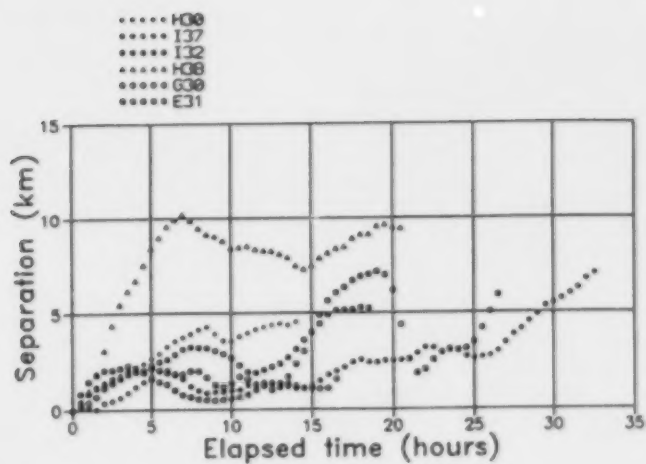


Figure 8 Separation distance versus drift time.

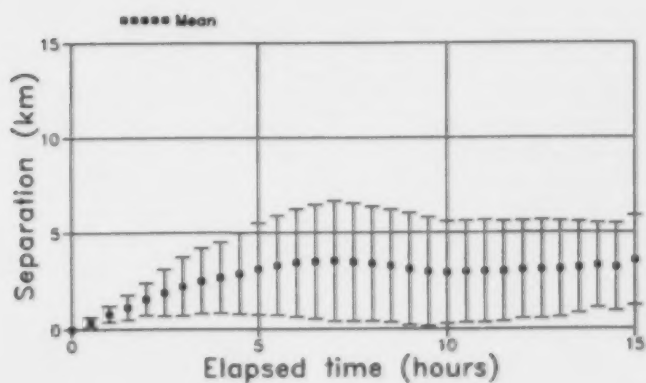


Figure 9 Average separation distance versus elapsed drift time.

the coverage area. Using the drifters to provide ground-truth data, the optimum radius for the Queen Charlotte Island deployment was 5 ± 0.5 km. Comparison of both radial and combined total current speeds and directions with individual drifter tracks showed a high correlation. In the coverage area the mean absolute difference between drifter currents and SeaSonde currents was about 7.8 cm/s with a standard deviation of 6.7 cm/s for currents ranging up to 80 cm/s. The results were essentially unbiased (mean difference of 0.25 cm/s and standard deviations of 10.3 cm/s). The drifter speed error is estimated to be about ± 4 cm/s based on the positional uncertainty of Loran-C in the study area.

A Lagrangian comparison showed that predicted drift from the SeaSonde data reproduced the tidally-induced eddies and loops exhibited by the drifters, as well as the overall drift patterns. The drifters were deployed for periods of 17 to 48 h. Characteristic separation distances in these times were about 5 to 7 km. The worst case from a drifter slightly outside the coverage area showed separations of 10 km within 7 h of release.

Based on linear regression of the separation distance with time for the three longest tracks, representative separation scales are 7 ± 1.5 and 9 ± 2 km for drift times of 36 and 48 h for targets within the coverage area of the radars. If the drifters are assumed to represent true positions, predicted drift with errors of this magnitude provide suitably accurate results for oilspill modelling. However, the drifters measure currents that are different from the SeaSonde, and some of the separation results from the differences in the currents as measured in each manner. Consequently, SeaSonde drift predictions for surface-floating objects may be more accurate than suggested by the drifter comparison. In order to better quantify the accuracy of SeaSonde predicted trajectories, a near-surface drifter with an effective penetration into the water of less than 2 m is required.

6.0 ACKNOWLEDGEMENTS

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The TENYO MARU Oil Spill: A Multi-Spectral Scanning and Sea-Truth Experiment

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ABSTRACT

The sinking of TENYO MARU off the Washington State coast caused an initial oil spill of about 100,000 gal. After response operations had contained and removed most of the spill, continued leakage from the sunken wreck provided an offshore source of freshly spilled oil at a known location. We conducted remote-sensing overflights, which were coordinated with collection of sea-surface slick samples, in an effort to test whether a multi-spectral scanner could accurately image a marine oil spill. Oil content in the sea truth samples ranged from undetectable to 180 mg, dependent on the local thickness of the slick. This variability was readily apparent in both the IR and UV bands of the scanner data and was detectable on a scale of meters. Chemical analysis identified two unique oils in the slick, one containing enhanced concentrations of toxic PAH. However, distinct signatures for these oils were not successfully extracted from scanner data. Distinguishing oil types on the water is theoretically possible, but would require greater density of sea-truth samples for confirmation. An integration of the data from multiple flight paths provided an overview of the distribution of thick and thin slick components in the vicinity of the wreck and illustrated the effect of an oceanographic front on controlling the dispersion of the slick.

INTRODUCTION

At 08:49, 22 July 1991, the Chinese freighter TUO HAI struck the Japanese fish processing ship TENYO MARU in heavy fog. The accident occurred in international waters within the Canadian Exclusive Economic Zone near the Strait of Juan de Fuca (Fig. 1). TENYO MARU was carrying 273,000 gal of bunker fuel and 91,000 gal of diesel fuel. The vessel sank in less than 10 min (all but one of the 85-person crew were saved) and spilled a combined total amounting to 100,000 gal of the two oils and an unknown amount of fish processing chemicals. The initial spill formed a triangular slick some 15 mi. wide; wind and currents subsequently carried it east and south toward the Olympic Peninsula of Washington. Tidal eddies then forced some of this slick off onto beaches of the Peninsula. Most of the beach oiling apparently occurred from 27 to 29 July. Many of the oiled beaches were in Makah Tribal land, so concerns of the Makah Tribal People had to be taken into account by both the official response team and by the sea-truth project team. Several Federal, State, Makah Tribal, and volunteer agencies were involved with animal rescue, rehabilitation, and census of dead specimens. The major slick continued to move south and disperse. Isolated tar balls were eventually reported from beaches in northern Oregon (Edwin Levine and Sharon Christoferson, NOAA-SSC, pers. comm.).

After the sinking, the wreck lay on the bottom in 530 ft of water at a reported position of 48°28.89' N and 125°17.12' W. Canadian Coast Guard reconnaissance with a remotely operated vehicle found the wreck upright with a 15° list and the stern portion broken free aft of midships (pers. comm. from Kevin Smith, CCG, 9 August 1991). The tanks breached in the initial breakup had evidently released an unknown quantity of oil into the overheads of the forward portion of the wreck. From there it migrated to the bow and escaped from two open portholes at a rate of about 500 gal per day or less. This slow, relatively constant release of oil formed a series of secondary slicks emanating from the wreck site. These secondary slicks were what was sampled by the sea-truth effort. Control of this release and containment of oil remaining in the wreck (estimated to be about 250,000 gal.) was the concern of salvage efforts headed by the Canadian Coast Guard.

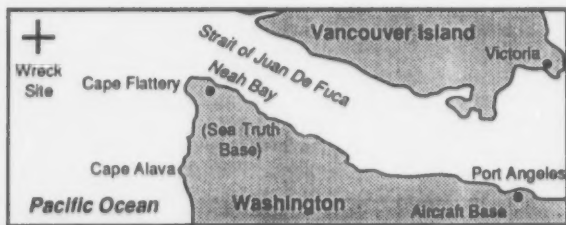


Fig. 1. Site map showing where the TENYO MARU sank and the general area of the scanner/sea-truth operations.

The Marine Spill Response Corporation (MSRC) recognized an opportunity to conduct a field study of remote sensing of oil spills that would aid in establishing logistic guidelines for future response efforts. The study was undertaken with the knowledge and consent of the U.S. and Canadian Coast Guards, NOAA, and Washington State officials including Makah Tribal authorities. The Environmental Research Institute of Michigan (ERIM) was contracted to provide scanner overflights. The Geochemical and Environmental Research Group at Texas A&M University designed and coordinated the overall field effort, collected sea-truth samples, and provided chemical analysis of the samples.

METHODS

All sampling at sea was conducted from chartered sport fishing boats on the 5th, 6th and 10th of August, 1991. Scanner overflights were made with twin-engine aircraft operated out of Franklin Field in Port Angeles, some 70 mi. from Neah Bay. When the airplane was overhead, the boat and the airplane could communicate easily on fixed-frequency FM radios. These radios were not adequate to reach from the boat to the airport at Port Angeles while the planes were still on the ground. To further complicate matters, the boat radios were also not adequate to reach Neah Bay once the peaks of Cape Flattery had been rounded. Initially, the instruction to launch the airplane was communicated by relaying a radio message via a second boat to a team member standing by in the

charter boat offices. The team member would then call the airfield offices and tell the plane to take off. This relay of messages resulted in predictable confusion—complicated still further by the fact that the airfield offices did not open until 9 am. A much smoother linkup was eventually obtained by calling a pay phone at the airfield directly from the boat via the Marine Operator on Vancouver Island. The importance of communications cannot be overstated in an operation such as this one.

Once the plane had taken off, the boat and plane would head toward the wreck coordinates or some other previously agreed location. The boat would mark the site and several points along the projected flight-line with flagged drogue buoys, to which were attached 4 ft sq pieces of foil-covered hard foam. The flags were intended to aid the boat crew in relocating buoys and worked well for this purpose. The foil squares were designed to be visible from the air and to show up as "bright spots" in the scanner records. In practice, visibility from the air was marginal at best.

Once the flight-line was established, the plane would fly and re-fly the line at various altitudes while the boat collected samples on the water. Two types of sample were collected: wipe samples of surface oil and water samples taken ~0.5 m beneath the surface. Wipes were collected at, minimally, 0.1 mi intervals along the flight-lines—more frequently if a variety of slick forms (e.g. mousse and floating tar balls) were present. Collections were also made at points along the flight-lines where no visible oil was present. During collection, a 5 by 30 cm strip of Nyltex mesh was secured with a stainless steel clamp to the end of a 2.5 m aluminium pole. Both clamp and strip were thoroughly rinsed with methylene chloride prior to collection. The strip was then gently placed on the surface of the water so that the floating slick would adhere to it, carefully retrieved to avoid contamination, and stored chilled in a clean (to EPA standards) 60 ml jar. Brief descriptions of the slick were recorded in the log during all collections. During the final cruise, collection of each wipe sample was recorded on a video tape annotated with both oral description and a time overprint. Care was taken to sample from the up-wind side of the boat and to extend the pole well beyond the boat's hull before placing the strip on the water.

Both the sea-truth and overflight operations were hampered by stormy weather throughout the experiment. The most effective efforts were achieved on 10 August 1991, when the aircraft collect 19 strip-images (12 at 1000 ft altitude and 7 at 3900 ft) of the slick while the sea-truth team collected 25 wipe samples and 5 water column samples while the aircraft was overhead (Fig. 2). A series of samples of beach tar were collected by a field team on 8 August.

The M7 optical system, used for the most effective scanner overflights, is an axe-blade type scanner that rotates to view a 90° swath beneath the aircraft. Sixteen spectral bands are collected between 0.357 and 12.110 μm . Scanner data were subject to a series of post-processing procedures to correct for aircraft roll, normalize the data to clear (un-oiled) water, to remove noise, and to calibrate the output.

Water-column samples were liquid-liquid extracted with methylene chloride using GERG standard operating procedures. Extracts were concentrated and weighed with and electrobalance. Water extracts were screened by gas chromatograph

with flame ionized detection (GC/FID) and polynuclear aromatic hydrocarbons (PAH) were quantified by gas chromatography/mass spectrometry/selected ion monitoring (GC/MS/SIM). Wipe samples and beach tar samples were extracted with methylene chloride, concentrated, and weighed by electrobalance. Samples were screened by GC/FID, selected samples were analyzed for PAH content by GC/MS/SIM. Other slick extracts were analyzed for quantitative biological markers.

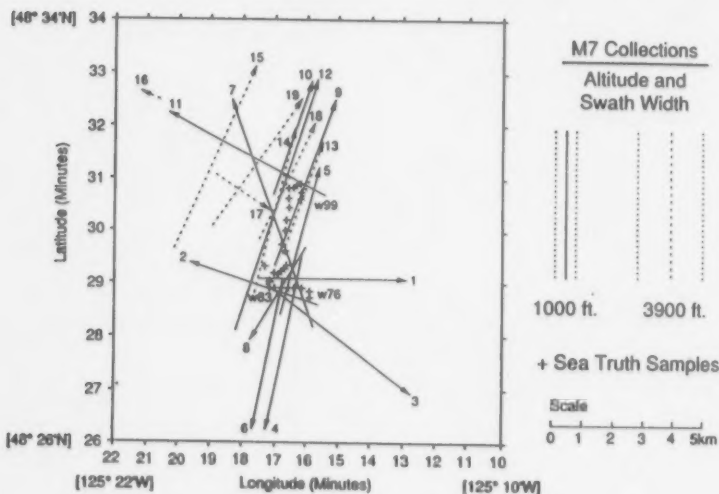


Fig. 2. Scanner flight-lines (arrows) and sea-truth samples (crosses) collected on 10 Aug. 1991 in the slick formed by oil leaking from the sunken wreck.

RESULTS AND DISCUSSION

Sea-truth Samples

The highest hydrocarbon concentrations observed in the water column samples were from samples collected directly beneath the visible slick, where total PAH's reached 2360 ng/l. Wipe samples of the slick provided a semi-quantitative estimate of the amount of oil on the sea surface and collected up to several grams of oil in some cases. Localized high values in areas of high oil volume illustrate the heterogeneity of the slick distribution and the consistent pattern of comparatively light and heavy oil on all three sampling days (Fig. 3)

Oil "fingerprints" (GC/FID) demonstrated that two distinct oil types were present in the slick emanating from the ship (Fig. 4). One fluid was predominantly normal alkanes typical of diesel fuel whereas the other fluid was enriched in polycyclic aromatic compounds, particularly lower molecular weight compounds. No known physical, chemical or biological process will produce such distinct

fingerprints from a single source. Observation of the two fingerprints throughout the sampling period suggests that two discrete sources of leakage were present on the sunken ship.

Six samples collected in a very limited beach survey were analyzed. All samples contained detectable hydrocarbons, but only one had high levels of PAH contamination. Interestingly, biological marker compositions indicate that the TENYO MARU slick was the source of this sample while eliminating the TENYO MARU slick as the source of the other samples. The presence of specific, unique markers in the majority of the beach samples can only be explained by the presence of sources of oil other than the TENYO MARU spill. In particular, five of the beach extracts contained oleanane and a peak tentatively identified as gammacerane. The TENYO MARU slicks contain neither of these compounds. Likewise the TENYO MARU slick contained tricyclic triterpanes, which were absent from the five samples. The beach sample with the highest level of fresh oil contained tricyclic triterpanes, but lacked oleanane and gammacerane.

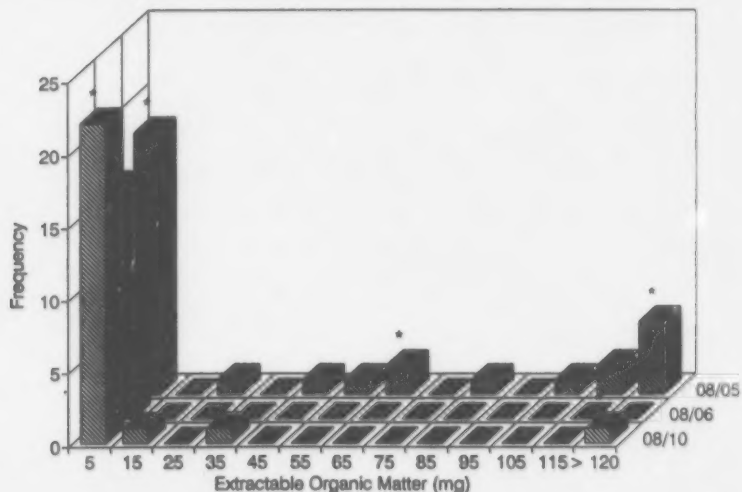


Fig. 3. Distribution of sample weights from slick samples collected during three days of sea-truth operations.

Multi-spectral Scanner Characterization of the TENYO MARU Spill

A composite image of two scan-lines (17 and 18) from 10 August documents the majority of oil present in the vicinity of the wreck on this date (Fig. 5). The distribution of the slick illustrates two components of the processes acting to disperse the leaking oil. Immediately over the slick, and for approximately 5 km to the north of the site, slick oil is confined to a wind-driven plume. This plume then intercepts a body of colder water and is entrained in a westerly current. The frontal boundary between the warmer and colder water was imaged by the infrared band of the scanner data and is estimated to indicate a 0.5 to 1.0 C temperature difference. This front acts as a natural barrier to the wind-drive oil,

with the result that oil has accumulated along the front. Interestingly, neither the aircraft team nor the sea-truth team were aware of this front and its effect on oil dispersion during the sampling operations. The sea-truth team followed the wind driven plume north from the wreck and failed to sample the thick oil that had been carried westward. The aircraft saw the thick oil along the front and assumed that this was the wreck site.

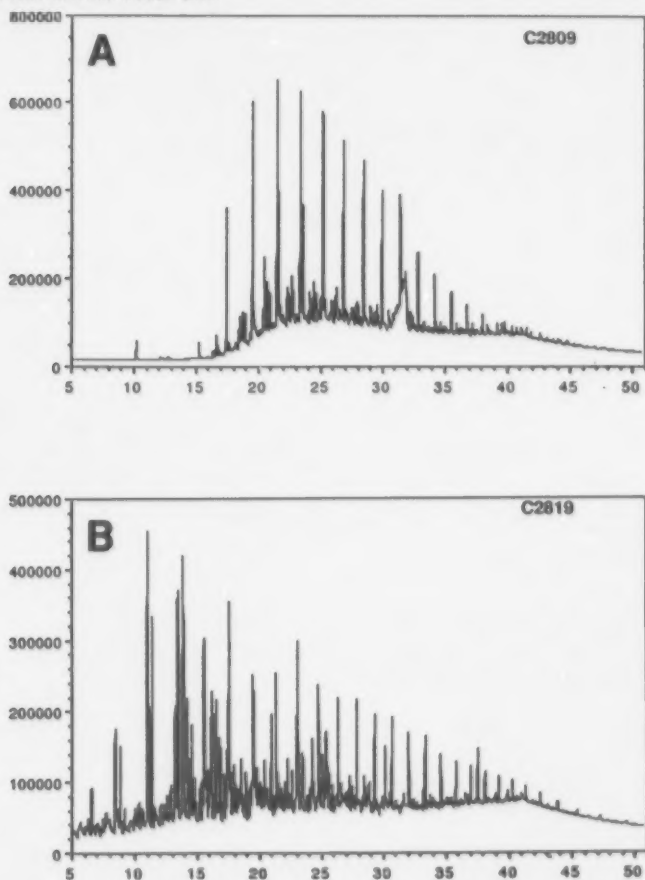


Fig. 4. Gas chromatograph fingerprints of the two types of oil detected in the slick: fingerprint A is typical of diesel fuel whereas fingerprint B is highly enriched in aromatic compounds. These two fingerprints could not have been produced by alteration of a single source.

The slick boundary on 10 August was defined by the ultraviolet (UV) channel. The total slick area observed covered approximately 450,000 sq m (Fig. 5). A strong infrared (IR) signature was observed along the nominally east-west portion of the slick. The areas with strong IR signature (negative contrast) covered approximately 100,000 sq m. Examination of the visible wavelength multi-spectral data revealed a reddish-brown color for oiled areas producing a strong (negative contrast) IR signature, which tended to confirm the presence of thicker oil. On this basis, the UV/IR channels appeared to do an excellent job detecting and ranking thickness for the thin slicks observed in Neah Bay. Interestingly only the long-wave IR (LWIR) channels operating in the 8-12 μm spectral region produced oil signatures. No significant IR signature was observed in the mid-wave IR imagery from the slick.

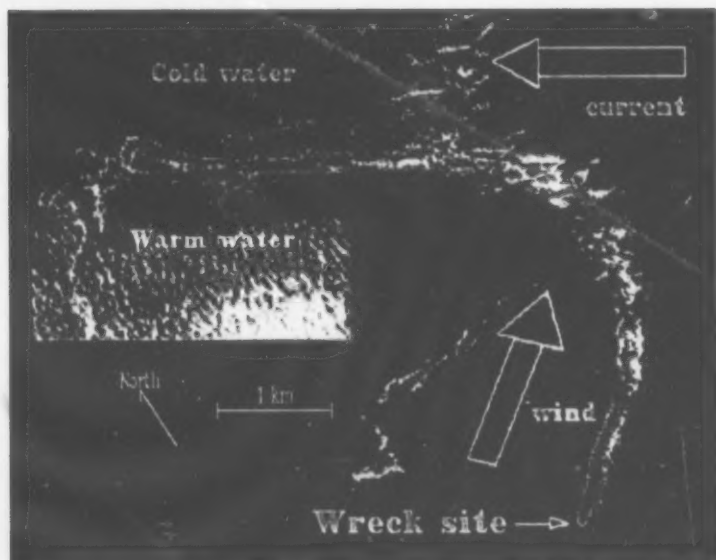


Fig. 5. Composite of UV/IR band scanner data from runs 17 (left) and 18 (right). Image shows a wind-driven plume being entrained in a westerly current. Thicker oil is evident along the frontal boundary between the two water masses.

During the first few days of August, the Canadian Coast Guard estimated the TENYO MARU leakage rate to be 500 gal/day based on observations from a submersible. Given estimated currents at the site (0.3 to 0.5 knots), the slick area probably represents about 125 gal of oil (6 hours release) yielding an average slick thickness on the order of 1 μm .

The results of this experiment were consistent with what was known about the spill. There were indeed two oils reported to be on board, the slick volume estimated from the imagery data was of the same order as the estimated leakage rate, and oil from the wreck was detected on the beaches. A number of lessons

were learned from the exercise. Communications and coordination between the sea and air teams was critical to success of the field effort, and reliable geo-reference data were equally critical for successful analysis of the scanner data. A better means for marking positions on the water in such a way that they show up in the scanner records should be found. Likewise, some method for obtaining continuous samples from the sea surface would alleviate some of the difficulties raised by the patchy distribution of the slick.

The imagery data were successful in resolving the processes that were dispersing the slick—processes not evident to observers who lacked the "big-picture" perspective. The chemical analyses were able to quantify the source and heterogeneity of the slick—and to detect pollutants that did not originate from the spill at hand. These successes indicate the value of these capabilities in a real-world response situation.

A REMOTE OIL SPILL DETECTION SYSTEM
FOR EARLY WARNING OF SPILLS AT WATERFRONT OR LAND-BASED
FACILITIES

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Abstract

Early detection of spills during loading/unloading of crude oil or products at terminals or plants is essential for quickly stopping the spill, thereby minimizing its impact. Such detection is particularly difficult at night or in remote areas. While a number of passive and active sensors have been discussed in the literature, no reliable, inexpensive system for this application has been identified in today's market. Thus, we entered into a joint development process with Spectrogram Corporation to re-design the Oil Spill Detection Buoy System, which had been successfully tested in the mid seventies.

The sensor's operation is based upon the stimulated fluorescence of oil and selective wavelength detection of this fluorescence. The prototype system consists of a flotation buoy for remote deployment of the sensor, rechargeable battery supply, a land based computer base station, and radio signal transmitter.

The oil spill detection buoy was modified in 1991 and lab tested early this year. Field trials are now underway at Exxon Company, U.S.A.'s Bayway refinery. Tests to date have confirmed the units ability to detect oil and to differentiate between various types of oil and/or products, particularly if the software is alerted to the type of product being transferred.

Introduction

The rapid detection of crude oil or petroleum based product spills during transfer operations is vital in minimizing the extent and impact of a spill. A market search by Exxon Research and Engineering in 1990 for oil spill detectors uncovered several potential devices that had been developed in past years. However, most of these systems were no longer in production or were not applicable in tidal or river current areas. One of the withdrawn systems, originally developed in the early seventies by the Spectrogram Corporation in North Haven, Connecticut, did appear to offer the desired features and detection capability. We subsequently contracted with Spectrogram Corporation to redevelop their technology, utilizing the most current materials and electro-optical components, and meeting or exceeding the current safety standards for hazardous environment deployment.

The oil spill detection buoy system, depicted in Figure 1, is comprised of a base station, and one or more sensor assemblies, with or without buoy platforms. The base station serves as the primary operator system interface and maintains full bidirectional communication with each sensor to assure fail-safe operation. Under the current design, up to sixty-four (64) detection sensors can be controlled and monitored by a single base station. The sensor assembly is contained in an explosion proof housing, which is also positively pressurized with an inert gas to protect the internal electronic components and eliminate ozone formation, as well as to provide an additional safety margin.

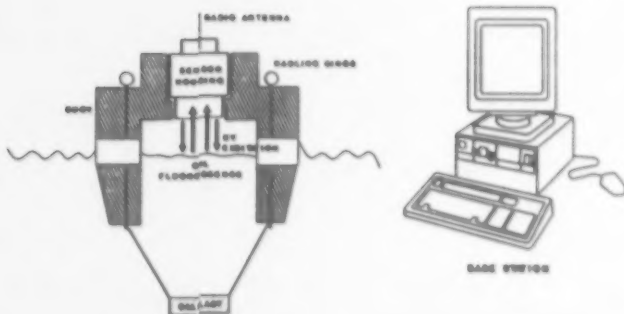


Figure 1. Oil Spill Detection Buoy System

Theory of Operation

Optical fluorescence is a phenomenon whereby certain materials will absorb short wavelength optical energy and re-emit a portion of the absorbed energy at a longer wavelength. It has been well documented that most petroleum based products exhibit optical fluorescence when irradiated by ultra violet light. The wavelength(s) and the amount of energy re-emitted from the excited sample tend to be specific to the particular molecular composition of the sample.

Crude oil and other refined oil products are detected and identified based on their property of fluorescing when exposed to an appropriate light (excitation) source. Selectivity between crude or heavy oils and lighter refined products is possible. Using a pulsed excitation light source, refined products such as gasoline, kerosene/jet fuels, and diesel fuel exhibit a major fluorescence response in the violet wavelength region. Crude oils and most heavier distillate cuts of crude, such as #6 Fuel Oil, and Bunker C exhibit a major fluorescence in the blue/green wavelength regions. Nominal background fluorescence of water borne biota appears in both regions.

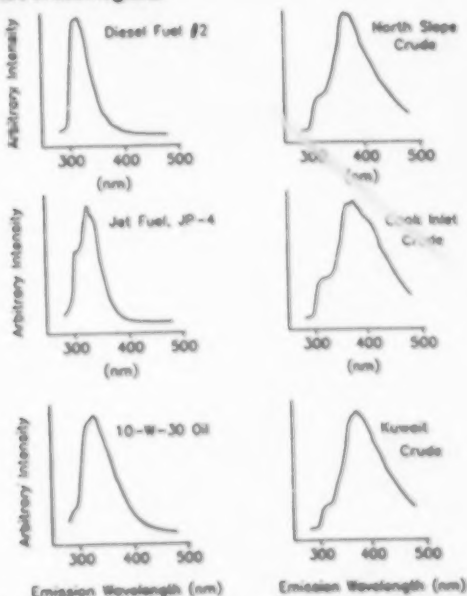


Figure 2. Typical Fluorescence Spectra at Constant Excitation Wavelength (254 nm)

Typical fluorescence spectra for light and heavy oils, collected using a 254 nm (nanometer) excitation source and measuring emissions between 280 nm and 480 nm wavelengths, are shown in Figure 2. Discrimination between the two groups of oil types can be accomplished through a signal processing scheme which ratios different wavelength responses. Background fluorescence is filtered out through a threshold "learning" algorithm, which distinguishes rapid fluctuations in the ratio slope versus gradual increases due to background buildup events.

The Spectrogram sensor assembly illuminates the water's surface with light from a pulsed ultraviolet mercury lamp. Collection optics split the received fluorescence signal into separate light beams which are directed to individual wavelength filters. The filters selectively pass a narrow wavelength band to a solid state photodetector. The detected signal is amplified, digitized, and further digitally processed by an onboard microprocessor. The processed data, as well as the sensor identification and certain diagnostic information, is then transferred to the Base Station microcomputer via a bidirectional communication (hardwired or radio transmission) link, for final discrimination and logging. Software at the base station performs the additional signal processing to determine if oil, and what type, has been detected. Visual and audible alert and/or alarm conditions are displayed to the operator. Local contact closures and modem/network connections are available to notify other personnel such as dock hands or transfer pump operators of an alarm condition.

Design Considerations

Marine terminal facilities in the U.S.A. are typically classified as Class I, Division 2 Hazardous Areas per the American National Standards Institute (ANSI)/National Fire Protection Association (NFPA) standards. In order to meet these requirements, the entire sensor assembly and rechargeable battery pack are enclosed in an explosion proof housing. As a further safeguard, the housing is positively pressurized using argon gas and sealed at the factory. An internal pressure switch disables the unit if the internal pressure drops below a set value. The sensor is turned on during deployment by tipping the sensor to its operating position. To prevent permanent damage to the rechargeable battery pack, the Base Station is alerted to a low battery condition and, after a short period of time, the sensor will automatically shut off.

The requirement to house the sensor in an explosion proof housing competes directly with our operability requirements for easy deployment and battery life. The desired sensor operating temperature range is from minus seven (-7) to plus fifty (+50) degrees C. Whereas the battery capacity is inversely proportional to the operating temperature, this also competes with the goal of prolonged unattended operational periods, particularly in the northern latitudes. Presently, to minimize the weight of the sensor, the selected batteries require recharging every 24

hours. Needless to say, for those site locations where portability is not required, the sensor can be hardwired and the power requirement is not a limitation. At the time of this writing, Spectrogram is looking to further optimize the sensor's electronic efficiency to dramatically extend the battery powered operating time. By designing the buoy to hold and retain the housing, the buoy can be left in the water while the unit is brought ashore for recharging.

The duty-cycle of the excitation lamp is limited to produce high peak ultraviolet radiation while maintaining a mean level well below the exposure threshold limit value for an eight hour period, ensuring complete skin and eye safety. During normal operation, the proximity of the lamp to the water surface eliminates any potential for personnel exposure. In addition, when the housing is turned over, the sensor is automatically disabled.

The sensor flotation (buoy) is constructed from a thick skinned, high impact and abrasion resistant foamed thermoplastic. Field tests have proven the stability of the buoy in currents up to five (5) knots and in moderate harbor wave conditions. Hydrostatic equations and modeling were employed to design a center of gravity far below the waterline with or without the sensor onboard (Figure 1). This gives the buoy a self-righting capability from any position. The buoy has five (5) equally spaced shallow windows across the waterline to allow flow beneath the sensor. The windows were given shallow depth to calm small wind waves passing through the buoy cavity. Corrosion resistant materials and protection methods are incorporated throughout the buoy. Maintenance is minimized to annual repainting of areas below the waterline for anti-biofouling purposes. In anticipation of contamination by oil spills, the buoy is easily disassembled for cleaning inner and outer hull surfaces. The buoy has met the key design goal of providing a durable and stable platform for the sensor, while minimizing the size and weight for ease of deployment.

System Operation

A typical early warning oil spill detection system consists of one Base Station, one or more buoy mounted Oil Sensors, and/or one or more fixed Oil Sensors located at other locations throughout the site. A single Base Station is capable of communicating with, and accepting data from, up to sixty-four (64) Oil Sensors. The communication between the Base Station and any sensor can be via radio frequency telemetry or by hardware cable. The communications data burst is very short, and a single radio frequency channel is sufficient for a given site. All data is encoded with checksums, and both the Base Station and sensor software will perform clear channel transfers within a fraction of a second. In the event of interference, data will be retransmitted until confirmation of a proper data packet is achieved.

The Base Station requests each sensor's status on a preset time schedule, and can at any time download certain operating parameters including alarm thresholds to each sensor. Although the Base Station software will make a final decision to alert the operator of an oil spill condition, any sensor will immediately interrupt the normal polling operation in the event that a fluorescent signal exceeds the downloaded threshold level. The Base Station will immediately request that the sensor increase its scanning rate and confirm the presence of the proper pattern for an oil spill. Upon confirmation, the operator will be notified that an alert condition exists, and if the signal persists for a preset period of time the Base Station will enter a full alarm condition. All of the above conditions can be adjusted to the site requirements at the time of installation.

During the normal polling operation, should a sensor not respond to a Base Station request for status, the operator is alerted to a potential sensor failure or loss of signal. As mentioned above, several internal operating parameters including battery status, are returned to the Base Station with each data packet. In the event of a sensor's immediate failure, the operator is again alerted so that the particular sensor can be replaced. Every effort has been expended to assure reliable, fail-safe system operation.

The Base Station maintains a transaction log of the incoming data which can be used to generate summary reports and plots of activity. This data can be archived to tape for long term storage. Equally the Base Station can be placed on a LAN network where the data can be viewed or transferred at a remote site. To further enhance the system capability, the inclusion of meteorological data, such as tide, temperature, wind direction, etc. is under consideration.

Field Testing Objectives

Field trials of the prototype buoy are underway at Exxon Company, U.S.A.'s marine facilities in New York Harbor. The primary objectives of these trials include:

- Confirm the unit's ability as an oil spill detector in actual harbor conditions.
- Develop the capability within the software to discern between an actual spill and random sheen appearance (e.g., bridge run-off during heavy rain storms).
- Determine optimum methods of deployment.
- Identify specific operations needs for the hardware and software.

- Test data telemetering in a number of situations (e.g., direct site, piping interference, distance, etc.)
- Monitor battery charging requirements.
- Define optimum number of sensors for typical installations.

Potential Applications

In addition to marine terminal applications, we envision a number of other potential applications for reliable oil spill detection devices. These include tank farms, pipeline valve stations, aviation fueling areas, truck and rail loading terminals, effluent discharge canals, municipal/industrial water intakes and others.

First Results of Airborne Trials of a 64-Channel Laser Fluorosensor for Oil Detection.

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ABSTRACT

A new 64-channel air borne laser fluorosensor for oil detection has been assembled and tested. During the Spring of 1992 a series of flights were made over various targets, comprising oil on water, on ice, and on simulated beach material. Some of the 64-channel spectral data are presented, and the implications of the spectral responses for classification and identification of oil, are reviewed, in the context of remote sensing of arctic and marine oil spills.

Introduction

The Earth's coastal and inland waters represent a major source of food, recreation and energy. Conservation of this resource requires monitoring systems which can provide both synoptic data on water quality and the real-time information required to deal with emergencies, such as oil spills. When oil enters the marine environment via deliberate dumping or disasters such as shipwreck, well blow-out or pipeline rupture, the affected areas are extensive, and often far from major centres, so that Airborne Remote Sensing must play a major role in damage assessment and the direction of clean-up. Both of these applications require rapid deployment of the equipment to the spill site and the timely dissemination of maps of oil coverage, including oil stranded on shorelines and amongst ice, as well as on water. Twenty-four-hour operation is essential, and weather restrictions should be minimal, and the false-alarm rate should be low. The requirement for 24-hour operation implies an active system, with its own energy source, and the chances of false alarms are minimized if the system observes oil directly, via the interaction of the source radiation with the oil molecules, especially if irradiating oil produces a distinctly different result than irradiating a clean area. Airborne Laser Fluorosensors, which irradiate the surface with a laser and observe the spectrum of the resulting fluorescence, were developed [1] specifically for this application, and their properties have been extensively studied, as reported in [2], [3], [4], [5], [6] and the citations therein.

The potential applications of the Laser Fluorosensor to spill clean-up appear to be:

- confirming oil-on-water reports by wide-area sensors;
- locating oil on ice and on shorelines;
- locating submerged oil.

The work cited above deals with detection and measurement of oil and other conditions on water, we report on testing relevant to detection of oil on shorelines, and on, and in, ice.

Equipment

The Laser Environmental Airborne Fluorosensor (*LEAF*) consists of a XeCl excimer laser, a 64-spectral-channel, range-gated receiver, and an operator console, which includes a datalogger. It is a self-contained package, requires a single operator, and is easily installed (Fig. 1) in any small aircraft having a 10-inch camera hatch. It has been developed with the support of a multi-agency, international group, lead by Environment Canada, and also contains units from an hydrocarbon-exploration joint venture between British Petroleum and Barringer Research Ltd.

The operating principle of the *LEAF* system is illustrated in the schematic block diagram in Figure 2. The laser and receiver optics are co-axial, so that they are aligned for all flying heights. The timing and energy of each laser pulse is monitored on output, as is the elastic backscatter from the surface, and the time-of-flight is used to control the range-gating of the receiver and to measure the aircraft altitude. In addition to fluorescence, the receiver collects some reflected sunlight; the correction is determined by gating the system 'ON' a second time, mid-way between laser pulses.

The fluorescence signals from each pulse are digitized, along with the laser energy for that pulse, altitude, time, aircraft position (LORAN/GPS), and housekeeping data, and written to a Data Cassette Tape. Averaged data, updated at 10Hz, are presented to the operator on a strip-chart and as annotation on the video from a downward-looking camera. This video, and the intercom audio, are recorded on standard 1/2-inch video cassettes. The *LEAF* has been designed specifically for airborne use, and embodies the experience from over 20,000 line kilometres of exploration flying with an earlier commercial instrument. The size, weight and power have been minimized to allow operation in small economical aircraft such as the AeroCommander (see Fig. 1). The principal parameters are listed in Table 1, and a detailed description of all sub-systems can be found in reference [7]. Compared to earlier versions, the *LEAF* system provides;

- the combination of spectral resolution (64, 5nm channels) with temporal resolution (20ns gatewidth, 2ns delay steps);
- programme control of range-gating;
- provision for in-flight measurement of dark-current and responsivity;
- provision to accommodate a dye-laser module and operate in 500-700nm region.

Fig. 3 shows some typical spectra from the flight tests.

Ground Tests

The receiver was radiometrically calibrated using a type DXW 1kw tungsten-halogen lamp, operated at 8.00ampere. The variation of signal strength with range was measured and is shown in Fig. 4; 1 digital unit (d.u.) = 0.5feet. The time-gating capability was used to measure the time history of the fluorescence of Alberta Sweet Mixed Blend crude oil, the same material used in the Ottawa flight trials described below. Fig. 5 shows spectra taken with delays of 10, 20, 30, and 40ns relative to the elastic backscatter. There is a noticeable red-shift with increasing delay; this is in agreement with Rayner and Szabo [8], who report the decay time of the 'red' fluorescence of crude oils to be about 2.5 times that for the 'blue'.

Table 1 - LEAF ParametersTelescope

Diameter	203mm
f/#	f/3.1
Field of View	1 x 3 mrad

Spectrometer

Optics	Catadioptric Czerny-Turner	
Grating(s)	600 l/mm, blazed @ 400nm 900 l/mm, blazed @ 525nm	
	<u>600 l/mm</u>	<u>900 l/mm</u>
Resolution	5.3nm	3.5nm
Spectral Range	328-665nm	530-710nm

Gatewidth	20 - 150ns
Gate Delay	+ 100ns (rel. to laser)
Gain Range	256:1 in 15 steps

Laser

Type	XeCl excimer @ 308nm
Pulse Rate	100pps
Av. Power	1 watt (max)
Peak Power	1Mw
Beam Divergence	1 x 3 mrad

Weight & Power

Power	< 50A @ 24 - 32VDC
Installed Weight	750lb

Flight Trials

In 1992, Environment Canada and the other sponsors funded a series of flight tests of the *LEAF* system over several targets. The *LEAF* was installed and operated by Barringer Research Limited in a small twin engine AeroCommander aircraft owned and piloted by Brucelandair International. Functional testing of the *LEAF* system was carried out over Lakes Ontario and Erie in 1991 and in the early part of 1992. Detailed evaluation flights were also flown in February 1992 over two controlled sites; (1) over contaminated and clean-water ponds at the Nanticoke refinery of Imperial Oil and (2) a multi-sample site, near Ottawa, Ontario. Environment Canada, Emergency Sciences Division, designed the test programme, supervised the building of the test site, and characterised the samples used as targets. The contaminated-water pond at Nanticoke was unfrozen and had oily material at the waterline and floating in one corner; the pond material was sampled, but has not yet been analyzed. The clean-water pond was frozen, with snow drifts at the edges.

The Ottawa site (Fig. 6) consisted of a series of ponds, separated by berms of rock-dust, specially built, for this test, in a quarry. The ponds were rectangular, either 20x50 or 40x50 feet in extent, and were arranged to form a rectangle, 240ft. long by 50ft. wide. The aircraft flew along the long axis of the rectangle, which was oriented approximately North-South. The berms between the ponds were painted with fluorescent paint, to delimit the samples both in the fluorosensor data and the track-recovery video. The larger ponds contained clean samples of water and broken ice, gravel and gabion rock, and sand, and the smaller ponds contained samples of the same materials, coated with Alberta Sweet Mixed Blend crude oil. The oil was applied at an average rate of $\sim 320\text{ml/m}^2$, which would imply a thickness of 0.3mm on a flat surface, but the actual thickness on the sand and gravel and ice was much less, due to the roughness of the surface. The ponds containing the oiled samples were lined with plastic film, coated with a layer of ice, so as to ensure that all of the oil remained in the pond, and could be removed, for safe disposal after the tests. The oil was applied just prior to the first pass by the aircraft, and areas 2 & 4 were re-coated as indicated in Fig.6. A total of 33 passes were flown, 13 between 12:00 and 12:40 EST and 20 between 15:40 and 16:49 EST. Of the 33 passes, 22 passed over at least one sample area and 15 passed over all the areas. In addition to supervising the construction, operations and clean-up of the test site, Environment Canada, Emergency Science Division, sampled the oil at regular intervals throughout the period and analyzed for weight loss and compositional changes, which will be reported on elsewhere [9].

RESULTS - Nanticoke

Figure 7a shows the time history of fluorescence across the edge of the Contaminated Sludge pond, the walkway separating the ponds, and the snow and ice in the adjacent clean-water pond. The traces are averaged over spectral bands, corresponding, from the top, to 'Red', 'Green', 'Blue', and 'Violet/UV'. Figure 7b shows single-pulse spectra for each of the regions. The reddish spectrum from the 'shoreline' of the contaminated pond resembles aged or heavy oil; the snow and ice spectra clearly show, in addition to a blue spectrum presumably due to dissolved impurities, the characteristic sharp Raman band of H₂O which appears at 343nm for excitation at the XeCl wavelength of 308nm.

Results - Ottawa

Fig. 8 shows a low-resolution profile over the test site, with each channel scaled to the same displayed height. The spikes in the 'RED' channel are fluorescent markers used to separate the samples; the spikes in the UV channel are from the exposed edges of the plastic sheets used to line the areas containing the contaminated material. Fig. 9 shows the spectra for individual pulses from the same line (#15) as Fig. 8, starting at pulse 80 of the second between 15:40:05 and 15:40:06 EST. Pulses #80 through #85 are from the first area of oiled ice (Area 7 of Fig. 6), Pulse #86 is the plastic liner, Pulse #87 is the fluorescent paint marker between Area 7 and Area 8, #88 & #89 are the liner, #90 through #96 are the second oiled ice, #96 is probably the plastic showing faintly through a thin film of oil, #98 is plastic, with a small red-orange peak, probably due to overspray of the fluorescent paint, and Pulse #99 is the final marker. Pulses are scaled to the same displayed height, the relative signal strengths are given by the second number in the second line of the header, and cover a range of 10:1. Successive pulses are about 60cm apart along the flight line; in normal survey operation, 10 pulses would be averaged to give 6m 'pixels', but the limited dimensions of the samples require the use of individual pulses.

Analysis

A principle objective of the test programme was to assess the capability of the LEAF to distinguish oil from natural backgrounds, such as ice and shoreline materials. While, in general, the oiled samples in the tests were clearly distinguishable by a much greater fluorescence intensity, it would clearly be unwise to rely on this alone. Also, there is interest in attempting to identify the age and type of spilled oil, to aid in determining its source. Several types of algorithms are being tested on the flight data. Fig. 10 shows the data from two passes over the Nanticoke ponds on a log-log plot of the Raman/Red ratio versus the spectrally-integrated fluorescence intensity. Each label represents the average over 10 laser shots, and is not corrected for variations in altitude or laser power. The various types of target identifiable on the ground cluster in non-overlapping groups on the plot.

While the principle effect of weathering, over the test period, is a reduction in fluorescence intensity, as shown in Fig 11, it is expected, on theoretical grounds, as well as the work of Raynor (loc. cit), that there should also be changes in spectral shape. The fluorescence spectra of oils resemble statistical distribution functions, and we are studying the use of moment functions to quantify small variations in spectral shape. Considering the 64 values of fluorescence intensity as a discrete function, $F(c)$, where c ($0 \leq c \leq 63$) is the channel number, its first moment, or mean, is

$$\mu_1 = \sum_{c=0}^{c=N} c \cdot F(c) / \sum_{c=0}^{c=N} F(c)$$

and higher moments are usually defined relative to the mean by

$$\mu_r = \sum_{c=0}^{c=N} (c - \mu_1)^r \cdot F(c) / \sum_{c=0}^{c=N} F(c)$$

Skewness, defined as

$$S = \mu_1 / (\mu_2)^{3/2}$$

may be visualized as a measure of asymmetry, -ve if the left side of $F(c)$ is larger, +ve if the right side. Fig. 12 shows preliminary results for the time history of the spectral skewness of two of the Ottawa target areas. The gravel, upper plot, was oiled only once, at $t = 0$, while the plywood was oiled at $t = 0$ and again at $t = 3.5$ hrs. The gravel shows an initial steep rise in skew, levelling out in the afternoon, while the plywood shows a rise each time it was oiled. A move toward more positive values of skew indicate the fluorescence is becoming bluer. The long term effect of weathering on oil fluorescence spectra has to be a reddening, since the lighter, more volatile, components fluoresce blue and the heavier, less volatile, red. However, in the short term, the situation is more complex, since there are also volatiles, such as alkenes, which absorb blue and UV and do not fluoresce. If a strong shortwave absorber evaporates rapidly, the oil will become more transparent, the fluorescent materials will see more laser photons, and the shortwave fluorescence will have a better chance to exit the oil without being absorbed. Raynor (loc. cit.) shows several crude oils which fluoresced bluer and more intensely after a short period of weathering, then faded and reddened in the longer term.

Conclusions

The analysis of data from the flight trials warrants the following conclusions:

- 1) In flights over the Nanticoke facility, the *LEAF* detected reproducible and distinct signatures from fresh oily material floating in a Contaminated Sludge pond, and the more aged material on the shore of the pond, the nearby roadway, and the snow and ice on an adjacent clean-water pond;
- 2) In small contained bodies of water, such as the sludge ponds, on a calm day, the surface may become so smooth that insufficient laser energy may be returned to operate the Lidar Altimeter. This effect is not a problem over open water; it was not encountered over nearby Lake Erie on the same day and the effect was only observed once, briefly, during 20,000 km of exploration flying over the North Sea, the English Channel, and the Gulf of Mexico;
- 3) In flights over the Ottawa test site, the *LEAF* measured reproducible and distinct signatures from gravel, gabion stone, sand, shallow fresh water, and ice, and from the same materials when coated with Alberta Sweet Mixed Blend crude oil: the oil was applied at an average rate of $\sim 320 \text{ ml/m}^2$, which would imply a thickness of 0.3 mm on a flat surface, but the actual thickness on the sand and gravel and ice was much less, due to the roughness of the surface;
- 4) In addition to the differences in spectral shape, the fluorescence from the 'clean' targets was distinguished by being between 10 and 30 times weaker than that from the same materials when coated with oil.
- 5) Changes in spectral shape due to weathering can be detected, from flight data, using simple algorithms, even from small areas which receive less than 10 laser shots per measurement.

Mention of commercial products and entities in this publication does not constitute an endorsement by the Government of Canada.

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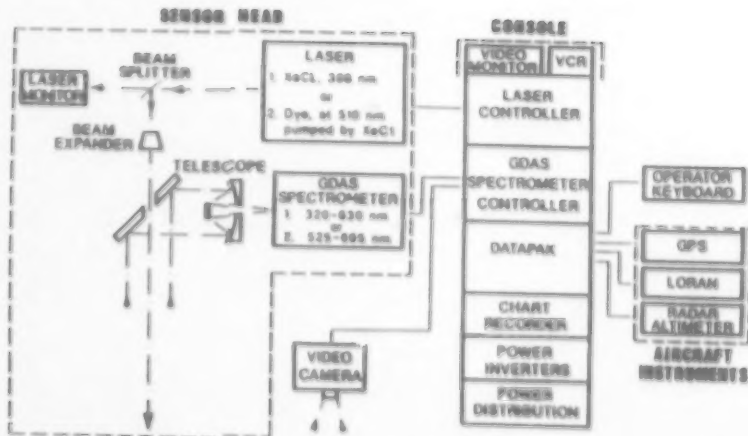
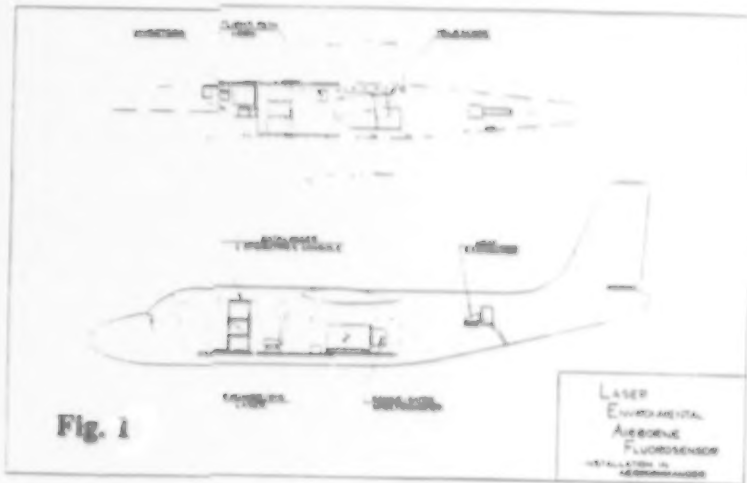


Fig. 2 FLUORENSENSE BLOCK DIAGRAM

Fig. 3 Typical spectra from test flights. From upper left these are, fresh crude oil, material on sludge pond, sand, gravel, snow, L. Erie water.

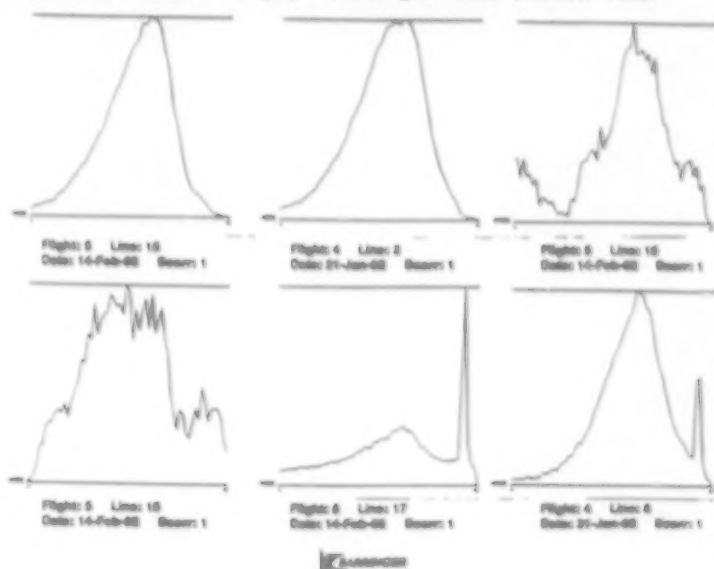
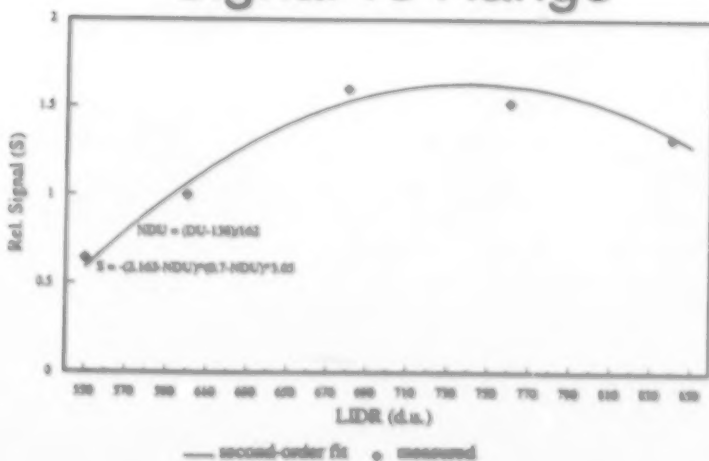


Fig. 4 Signal vs Range



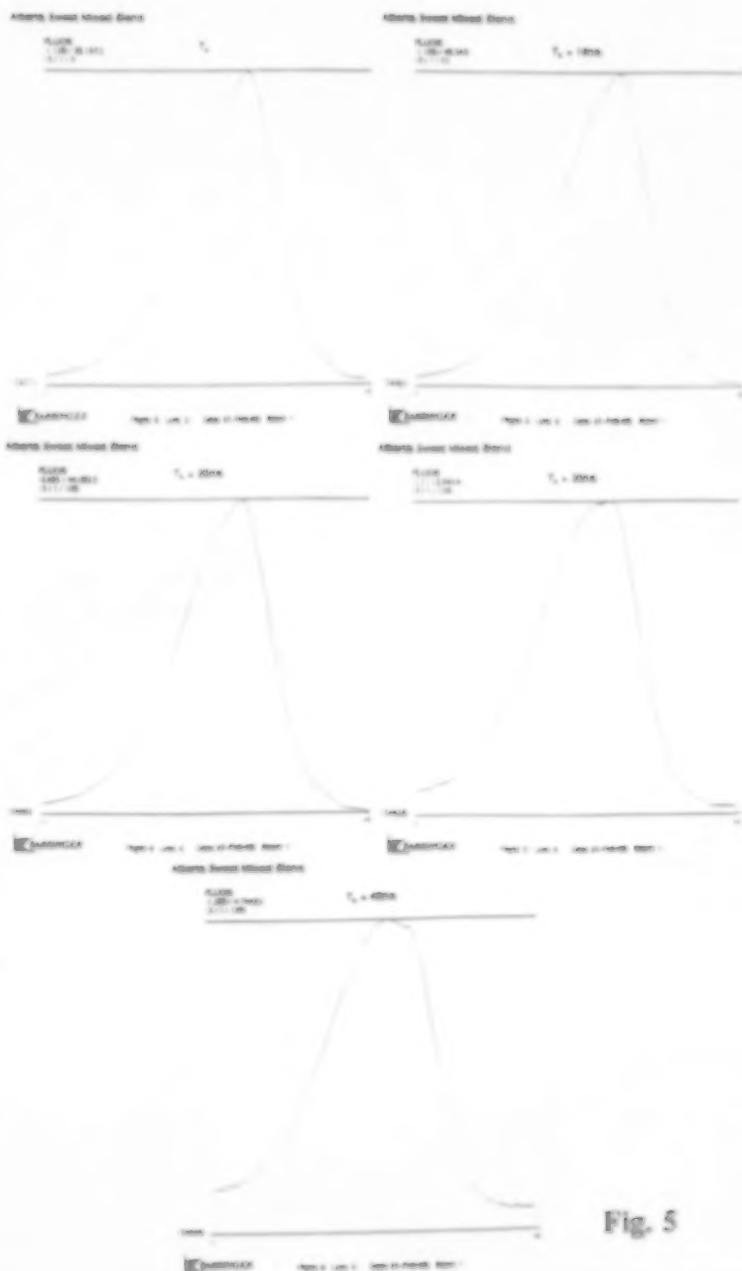
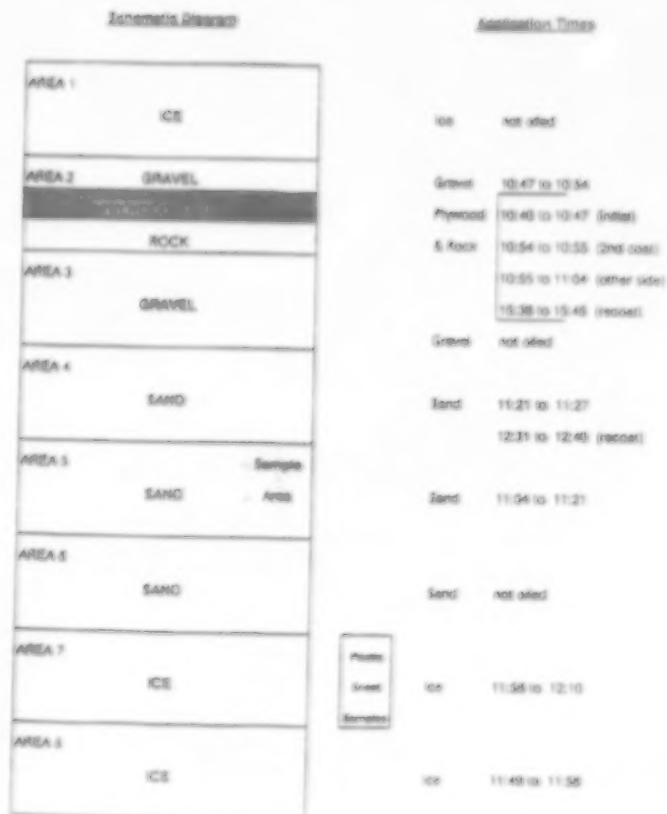


Fig. 5

Fig. 6

Remote Sensor Test: Schematic Diagram and Oil Application Times



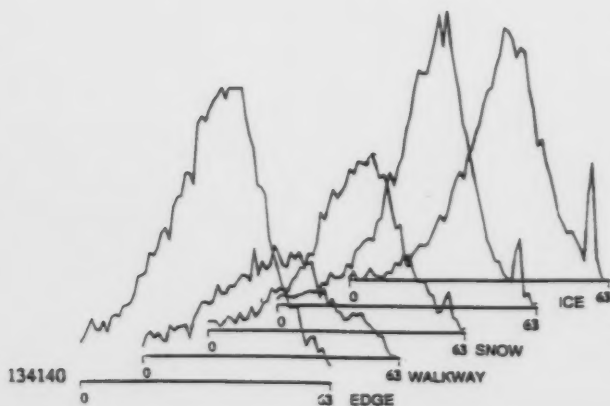
Nantuxie : Sludge pond & clean pond

FLUOR-25-18
0 / 150
15 / 15 / -102FLUOR-19-37
0 / 150
15 / 15 / -102FLUOR-38-24
0 / 150
15 / 15 / -102FLUOR-57-40
0 / 150
15 / 15 / -102

BARRINGER

Flight: 4 Line: 4 Date: 31-Jan-92 Score: 1

Fig. 7a

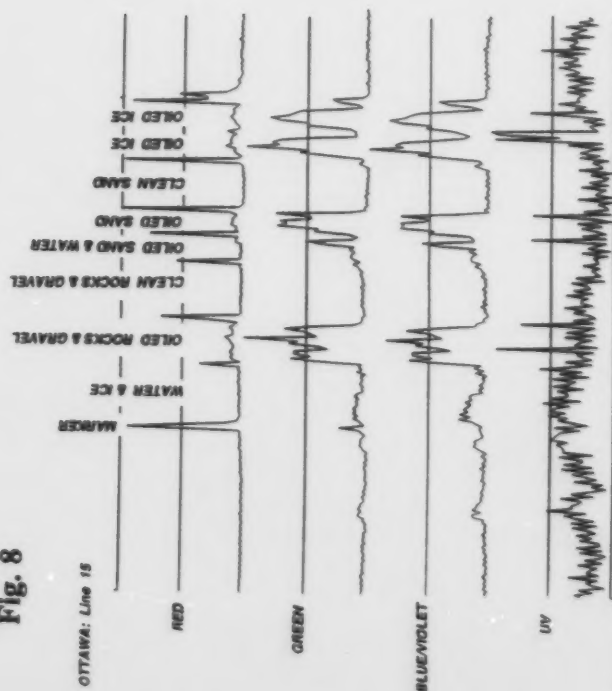


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Fig. 7b

Fig. 8



BARRINGER Flight: 6 Line: 15 Date: 14-Feb-82 Bcorr: 1

Fig. 9

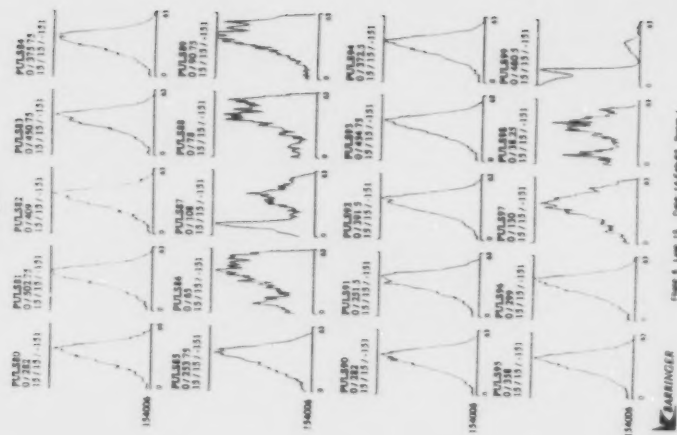


Figure 5, Line 15 Date: 14-Feb-82 Bcorr: 1

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SIGNATURE CLASSES

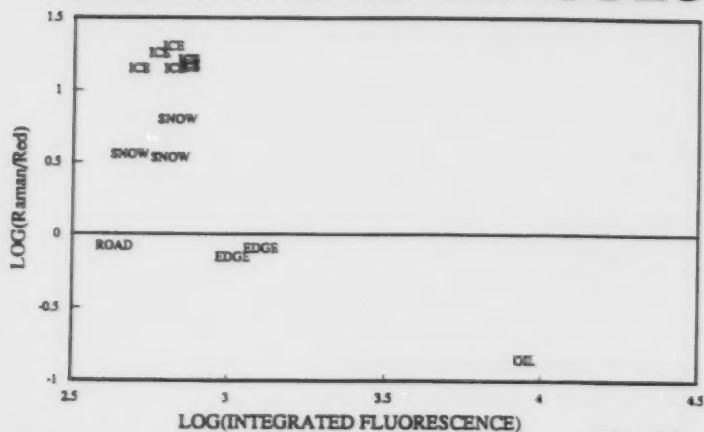
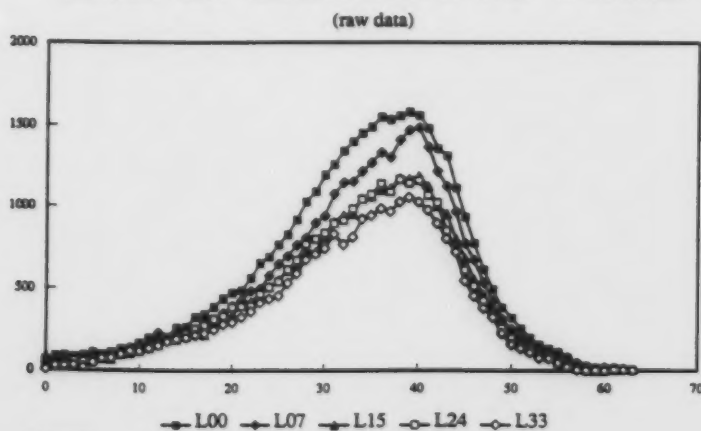


Fig. 4

Fig. 10

OIL SPECTRA vs TIME

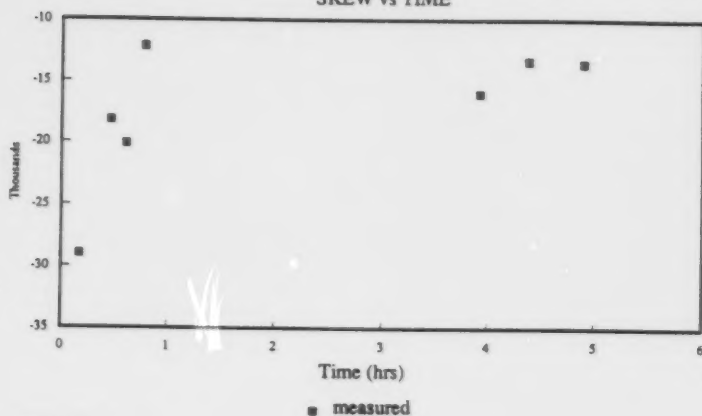


Feb. 14/02/92

Fig. 11

OIL SPECTRAL CHANGES

SKEW vs TIME

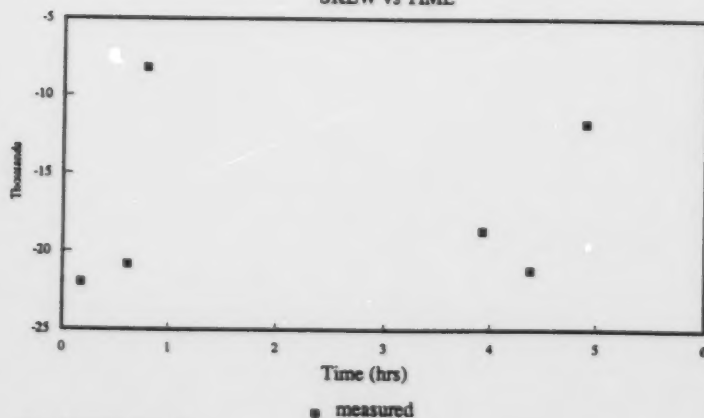


OIL on GRAVEL
Pb5, 1402/92

Fig. 12

OIL SPECTRAL CHANGES

SKEW vs TIME



OIL on PLYWOOD PYRAMID
Pb5, 1402/92

OIL SPILL MODELLING USING REMOTE SENSED SURFACE CURRENTS

By

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ABSTRACT

Surface currents measured in Queen Charlotte Sound with the SeaSonde HF radar were used in conjunction with the SPILLSIM oilspill model to predict the character of hypothetical oil spills. A comparison between these spill model results, and predictions based on best-available current and wind input in the absence of the radar measurements, revealed that simple tidal model + wind forcing leads to serious slick prediction errors, including speed and direction of drift, and area of ocean swept by oil. The consequences of these prediction errors include serious mis-interpretations of the tendency for oil to come onshore, and the timing, position and extent of shoreline fouling if the oil does tend toward land. Remotely sensed surface currents using HF radar offer a significant improvement in forecasting spill motion in real-time.

1.0 INTRODUCTION

1.1 Study Background

SeaSonde is a high-frequency radar capable of remotely sensing ocean surface currents from two or more locations on shore, with ranges exceeding 60 km. These radars provide coverage exceeding 2,000 km², and the data are ideally suited to calculating oilspill motion on the open ocean (Hodgins, 1991). Previous studies of the accuracy of the SeaSonde surface current maps have shown that the data measure the essential features of the surface flow, such as eddies, tidal loops, frontal shear and zones of upwelling and downwelling at scales larger than the range ring spacing of the radar (2.55 km). Comparisons made with current meters and drogued drifters (e.g. Lawrence and Smith, 1986, Hodgins and Hardy, 1992a) indicate that the currents measured with HF radars using direction finding methods generally agree with other measurements to within ± 5 to ± 8 cm/s in currents ranging from < 0.05 m/s to more than 1 m/s, with good agreement for direction. The Lagrangian experiments described by Hodgins and Hardy (1992a) also showed good agreement in drift trajectory, with typical separation scales of less than 10 km after 48 h. These and other studies have established the validity of the SeaSonde currents.

In many coastal areas surrounding Canada, information on surface flows are lacking. Moreover, the surface circulation is notably variable, responding to tides, winds, density variations, and low-frequency shelf waves. A great deal of this variability is not predictable with present numerical models, but can be measured using SeaSonde. One part that can be estimated is the barotropic (depth-averaged) tidal current. A finite element model (Foreman et al., 1992), which provides estimates of the barotropic flow field for several tidal harmonic constants, has been applied to the north coast of British Columbia. The model has good spatial resolution in the radar coverage area around Cape St. James.

In this study a comparison is made of oilspill trajectories modelled with surface currents measured with the HF radar against trajectories modelled using the depth-averaged tidal currents, derived from the finite element (FE) model, to which a surface wind-drift current has been added using locally measured winds. The model-plus-wind current approach characterizes about the best one can do in many coastal locations in Canada. The purpose of this study is to examine the nature of errors that arise from the simplified approach, and to comment on the benefits gained from the use of remotely sensed data for emergency response.

1.2 Environmental Data

Details on the deployment of the SeaSonde radars, the data processing to give surface current fields, and the comparison with drifter data are given in Hodgins and Hardy (1992a). Examples of two flow fields are presented in Fig. 1 illustrating the comparatively smooth, curvilinear field characterizing ebb tide, which is reasonably well predicted by the FE model, at one time, and the formation of a distinct eddy, at a later time. The latter feature is difficult to model, but is important to oil dispersion.

The oilspill modelling region has been defined by a 1 km by 1 km Cartesian grid shown in Fig. 2. The SeaSonde coverage area is shown embedded in this grid. The SeaSonde surface currents were extrapolated to fill the remainder of the grid using the average u and v components calculated from the eight surrounding points for each cell outside the coverage area. At least three points must enter the average, and no attempt is made to satisfy flow continuity, nor to account for coastline influences on the direction of flow. Near the radar coverage area this method provides a reasonable extension of the measured currents. Further away the approximation breaks down, particularly near the coast; however, the method provides a convenient, rapid procedure for preliminary fields. The errors will have minimal effect for oilspills released near the coverage area.

The tidal currents from the FE model (supplied to this project by Dr. M.G.G. Foreman, Institute of Ocean Sciences, Fisheries & Oceans, Canada) were reconstituted from their ellipse parameters at each grid point. A comparison between the tidal data calculated on the irregular FE grid, and

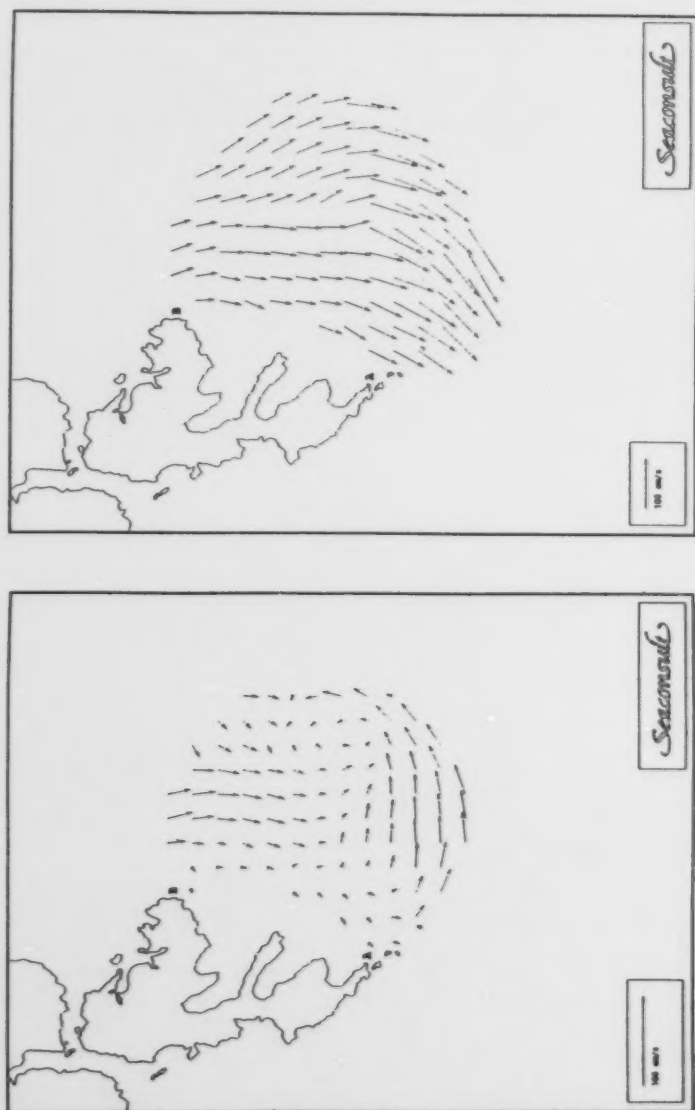


Figure 1 Examples of surface current fields measured by SeaSonde in Queen Charlotte Sound.

the corresponding Cartesian current map showed that the agreement in magnitude and direction was generally good for the stronger regions of flow (Hodgins and Huang, 1992). Differences becomes slightly more pronounced in the weaker regions, likely arising from the interpolation of ellipse parameters in an area where the irregular mesh has become large compared with the Cartesian grid.

Hourly winds were measured at the weather station on Cape St. James (elevation approximately 100 m) throughout August. Wind-driven currents were added to the tidal currents using a reduced wind speed calculated from the relation $U_{10} = U(z) (z/10)^{-1/10}$, with $z=100$ m. The direction was assumed to be unmodified, and the resulting vector was applied uniformly over the model grid. The current component was calculated using the model of Samuels et al. (1982), i.e.

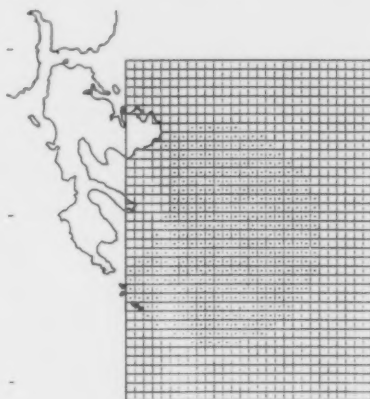


Figure 2 Spill model grid.

$$U_w = 0.035 U_{10}$$

$$\text{and } \theta = 25.0 \exp(-U_{10}^3 \times 10^{-8}) / (\mu g)$$

where θ is the deflection angle off the wind vector, μ is the kinematic viscosity at 15°C (1.2×10^{-6} m²/s) and g is gravitational acceleration.

1.3 Modelling Strategy

In order to illustrate differences in oilspill predictions, two spill scenarios were chosen: (1) an instantaneous release of 10,000 bbl of oil (1,590 m³), and (2) a 10-h continuous release of 10,000 bbl. The second, continuous release serves to emphasize the differences in dispersion produced by both phase and amplitude differences in the forcing currents. Spill locations and the times of initial release were selected so as to keep an oil slick in the coverage area for as long as possible.

Oil properties for North Slope crude, presently carried by tankers down the west coast of British Columbia, were used. The parameters are:

Oil Type	North Slope (Alaska)
Crude	
API gravity	26.4
Density (g/cm ³)	0.896
Viscosity (cp)	26
Initial boiling temperature (°K)	333
ASTM distillation gradient	707
Vapour pressure (atm)	0.245

The initial boiling temperature and ASTM distillation gradient were derived from Nelson's data for crude oils (Mackay and Paterson, 1980) with an API gravity value of 26.4.

The surface current dataset yielded two, quite different conditions: onshore winds during a storm on August 7-8, and offshore winds between August 15-24. The simulations were selected to model each condition, and were initialized as follows:

Simulation Time	SeaSonde Data Duration(h)	Release (GMT)
On-shore winds 23:00	15	91-08-07
Off-shore winds 02:00	40	91-08-17

The release times apply to both the instantaneous and continuous spill scenarios.

Comparison of the trajectory predictions from both current simulations has been made in terms of three parameters: - the trajectory of the centre-of-gravity of the slick; - total water area swept by the slick; - length of shoreline oiled. In addition to these quantitative parameters, plotted oil distributions were also used for comparison: instantaneous slicks defined by the volume in each cell of the model grid at specific times, and the swept area of sea surface, portrayed by the maximum volume of oil occurring in each grid cell over the full drift period.

2.0 DESCRIPTION OF THE OILSPILL MODEL - SPILLSIM

The spill simulations were modelled with the trajectory and fate model SPILLSIM described by Hodgins et al. (1991). The model treats both advection and spreading of oil, as well as weathering. Evaporation is modelled using the analytical method based on an equation for the vapour

pressure as a function of both temperature and fraction evaporated (Mackay and Paterson, 1980). In this method the oil is parameterized in two components, the "thick" portion of the slick, and the "thin" portion (Mackay et al., 1980), and the other weathering processes are parameterized consistently in terms of the same two components.

The spills were described by a single parcel of oil, in the case of the instantaneous releases, or as a time-series of discrete parcels in the case of continuous release scenarios. In the model formulation each parcel has a volume and area associated with the thick and thin slick components; these volumes and areas change as a function of the weathering processes. Horizontal dispersion of the oil was modelled by dividing each parcel into many particles. The oil volume associated with the parcel at any time is divided equally amongst the particles in order to account for shoreline, and other boundary volume losses.

The advective effects are determined by the currents, while the influence of turbulent diffusion is modelled as a random process. The oil particles are dispersed by the currents independently. Each particle of oil is defined by a position vector $R(t)$ with location at time t given by:

$$R(t) = \int_0^t (U_c + U') dt \quad (2.1)$$

where U_c denotes the smoothly varying current comprised of (1) the SeaSonde derived surface current, or (2) the tidal current plus the wind-driven current.

The turbulent part of the flow field U' arises from subgrid scale motions that are not resolved in the smoothly varying part of the flow, and from variations associated with changes in wind speed that are not contained in the wind field. The integral in (2.1) is solved in a sequence of N discrete time steps with increment Δt , for M particles comprising each oil parcel spilled. The result is M position vectors

$$R_i(N\Delta t) = \sum_{n=1}^N (U_c(n\Delta t) \cdot \Delta t + x_n \cdot r_n); \quad i=1,2,\dots,M \quad (2.2)$$

where r_n is a random number in the range $(-1,1)$. For a particle that moves a distance which is uniformly distributed in the range $(-x, \dots, +x)$ in a time step Δt , the probability of the particle being at location x at time t satisfies the diffusion equation. Representative diffusion coefficients are specified as a function of a length scale (Monin and Ozmidov, 1985) characterizing the turbulent process omitted from U_c . The diffusion coefficient in the present study was $10 \text{ m}^2/\text{s}$. This solution procedure constitutes a Monte Carlo

method (Bauer, 1958) where the diffusive effects of U' are simulated by a random walk analogy (see e.g. Tayfun and Wang, 1973) consisting of M trials each with N random displacements having magnitudes between 0 and x .

The oilspill model was applied on the 1 km by 1 km grid shown in Fig. 2, comprised of 28 columns and 38 rows. The integration time step was 120 s, which is sufficiently small to provide accurate estimates of evaporation as well as of advection using the simple one-step predictor method for transport given in (2.2).

The weathering processes are treated in terms of the volume and area of oil associated with each parcel, modelled in terms of the thin and thick slicks. The slick properties are area, volume, and thickness for both component slicks, and the total area, total volume, and per cent volume remaining.

Spreading is modelled by an initial period of gravitational spreading governed by the inertia of the slick (Fay, 1971), which yields an estimate of the initial thick-slick area. Subsequently, the method described by Mackay et al. (1980) is used, expressing the change in area of each component slick with time. The thin slick thickness is treated in this second stage as a constant (10^{-5} m).

Evaporation of hydrocarbon spills comprised of several fractions is modelled by volume losses from both the thick and thin slicks. The volume change of the thick slick is based on the evaporative exposure concept described by Stiver and Mackay (1984). Denoting f_c as the volume fraction of evaporated liquid, it is defined at any time t as $df_c = H \cdot d\theta$, where $\theta = K_e t/h_c$ = evaporative exposure as a function of t , the mass transfer coefficient K_e and slick thickness h_c ; and $H = P \cdot M_e / (R \cdot T) = \exp(A - B \cdot T_b/T)$ in which A and B are constants derived from experimental data.

For various crude oils typical values are $A = 6.3$ and $B = 10.3$. T_b is the boiling temperature ($^{\circ}\text{K}$) which is related to the initial boiling temperature T_{b0} , f_c , and the gradient of the distillation curve T_g by $T_b = T_{b0} + T_g f_c$. The expression for T_g is $T_g = C T_b / 10.6$ with $T_b = 283^{\circ}\text{K}$. Representative values for C are available from Mackay and Paterson (1980) for crude oil and several oil-based products.

In the above equation T is the air temperature ($^{\circ}\text{K}$) at which the vapour pressure P is calculated, and R is the gas constant ($82 \times 10^{-6} \text{ atm} \cdot \text{m}^3 \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$). M_e is the molar volume of the fraction evaporating. For various oil products Mackay et al. (1980) recommend values ranging from 100 to $250 \times 10^{-6} \text{ m}^3/\text{mol}$. The vapour pressure P is defined by $P = P_0 \exp(-C f_c)$, where P_0 is the initial vapour pressure.

The mass transfer coefficient K_e is given by $K_e = 0.001815 (W_{10})^{0.78}$, where W_{10} is the 10-m overwater wind speed in m/s. The volume of oil evaporated in time step Δt is thus (Mackay et al., 1980)

$$\Delta V_e = -V_e \cdot \Delta f / (1 - f_e) \quad (2.2)$$

Evaporation from the thin slick is assumed to be instantaneous reaching the limiting value f_{max} immediately, i.e.

$$\Delta V_n = -V_n \cdot (f_{max} - f_n) / (1 - f_n) \quad (2.3)$$

The emulsified oil properties are calculated from the change in water content of the emulsion, which is a function of wind speed (Zagorski and Mackay, 1982). Dispersive losses are also taken into account.

Shoreline cells are defined on the landward side of the solid boundary marking land from water cells. These shoreline cells are assigned an oil saturation volume depending upon their morphological composition. During the advection process, each particle may cross from water into a shoreline cell in one time step Δt . The volume assigned to that particle is absorbed by the beach cell, and the particle is removed from the numerical integration, until the cell is saturated. If additional particles enter the shoreline cell after it has reached saturation, these particles are returned to the adjacent water cell with their volume intact. In this way the volume of oil retained on the shoreline during a spill simulation is accounted for in the total volume of oil at any time t . For spill modelling in Queen Charlotte Sound a low value of $0.001 \text{ m}^3/\text{m}$ of shoreline has been used corresponding with rocky, high-energy coastal zones.

At open boundaries the transport model is programmed so that if a particle moves across the boundary and out of the solution domain, the particle volume is lost permanently.

3.0 EVALUATION OF OILSPILL TRAJECTORY PREDICTIONS

3.1 On-shore Winds with Large Tides

Tides during the on-shore wind simulations ranged over 3 m in elevation, producing currents exceeding 60 cm/s in the centre of the coverage area. A comparison of the u - and v -components of the SeaSonde surface current with the tide+wind components is shown in Fig. 3. The SeaSonde data are well correlated with the modelled currents until about 03:00 GMT on August 8, at which time substantial differences arise, likely associated with the response of the large-scale circulation in the Sound and Hecate Strait to the intense extratropical storm that passed over the area.

Both the instantaneous and continuous release scenarios showed similar behaviour for this simulation. The northwestward trajectories of the centre of mass for the instantaneous spill (Fig. 4) are similar over the first 6-8

hours after release, consistent with the well correlated currents during this period. Thereafter, the tide+wind prediction continues to move onshore, and extensive shoreline contact is predicted. The SeaSonde currents produce a different result, with the oil remaining offshore, without contact along the coast.

The oiled swaths are shown in Fig. 5 for the instantaneous oilspill. In the tide+wind forcing case, the total sea area swept is 139 km² compared with 181 km² for the SeaSonde currents. In the former case, 10 km of shoreline contact are predicted versus no contact with SeaSonde.

The continuous-spill centre of mass trajectories are compared in Fig. 6; the main difference is the greater tendency for the tide+wind forcing to bring the oil onshore, consistent with the previous findings. Slick position and coverage is compared at elapsed times of 9 and 12 h in Fig. 7 and 8.

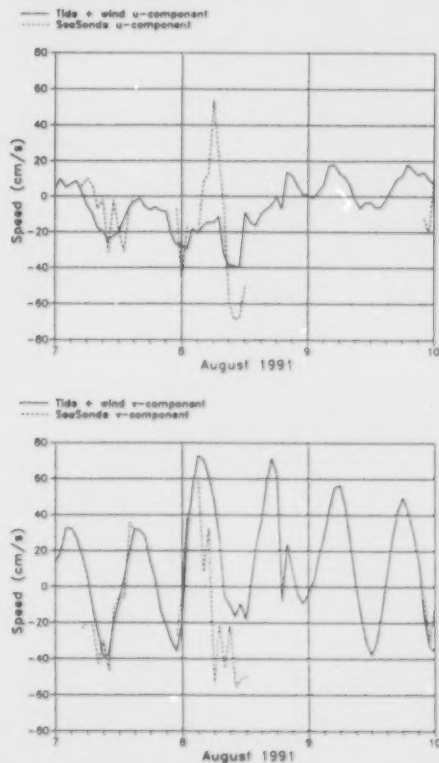


Figure 3 SeaSonde versus tide+wind currents.

During the period of similar currents, the coverage is roughly the same; however, over 9 h the tide+wind forcing produces the greater excursion with oil predicted to reach shore. This trend is modified in the SeaSonde simulation by the weakening currents and flow back over the release site at 9 h. After 12 h the trend of the tide+wind simulation is clear: the elongated oil slick is predicted to move down the coastline, threatening the shoreline resources. In contrast, the SeaSonde prediction shows the oil remaining offshore, moving south to the open sea without contacting land.

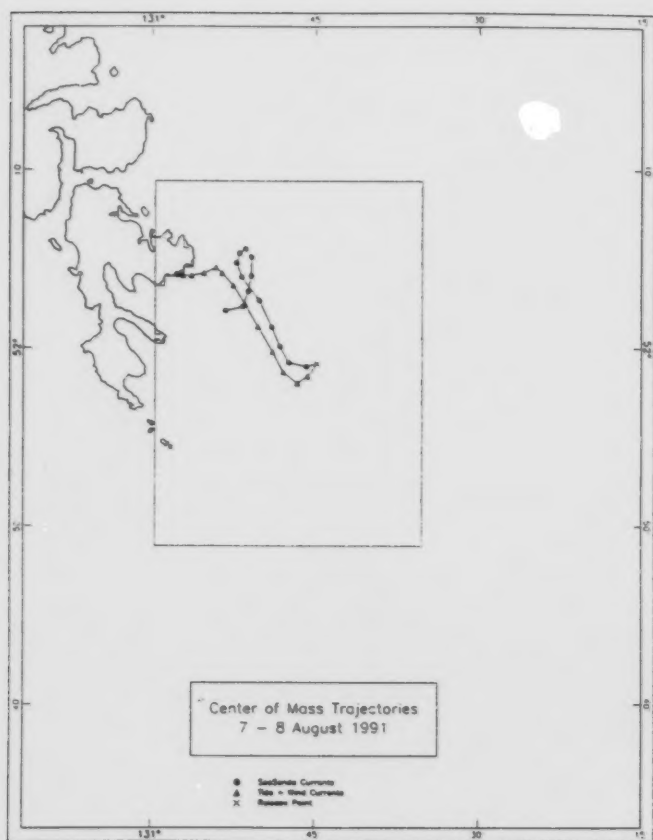


Figure 4 Comparison of centre of mass trajectories for the instantaneous spill with on-shore winds.

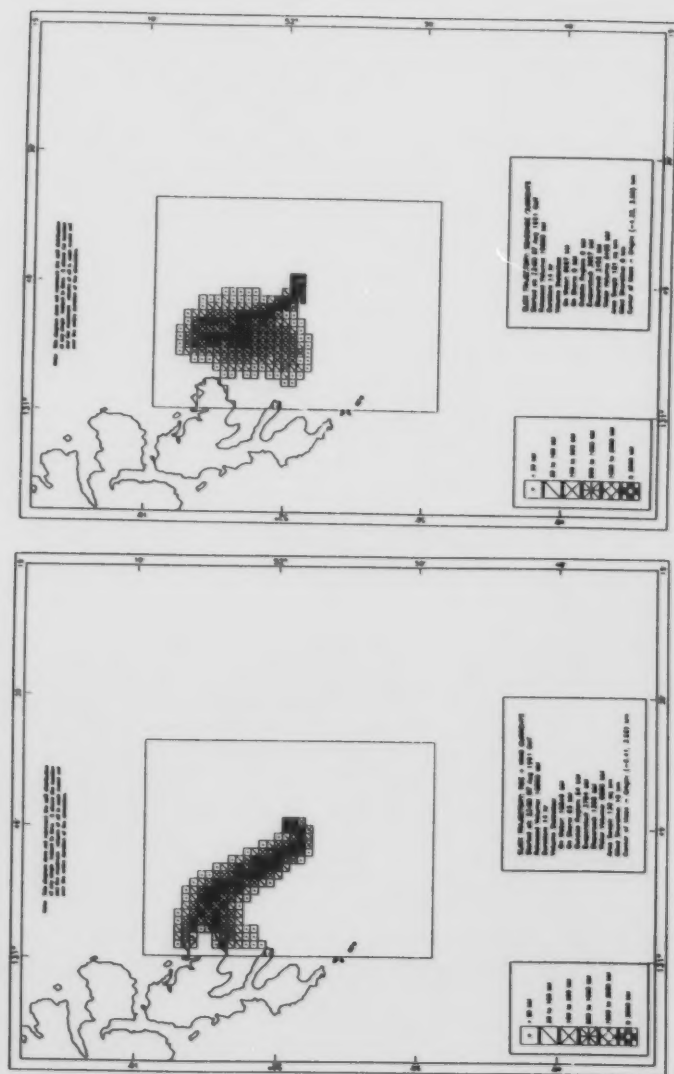


Figure 5 Oilspill swaths for the instantaneous spill with on-shore winds: tide + wind (left) and SeaSonde (right).

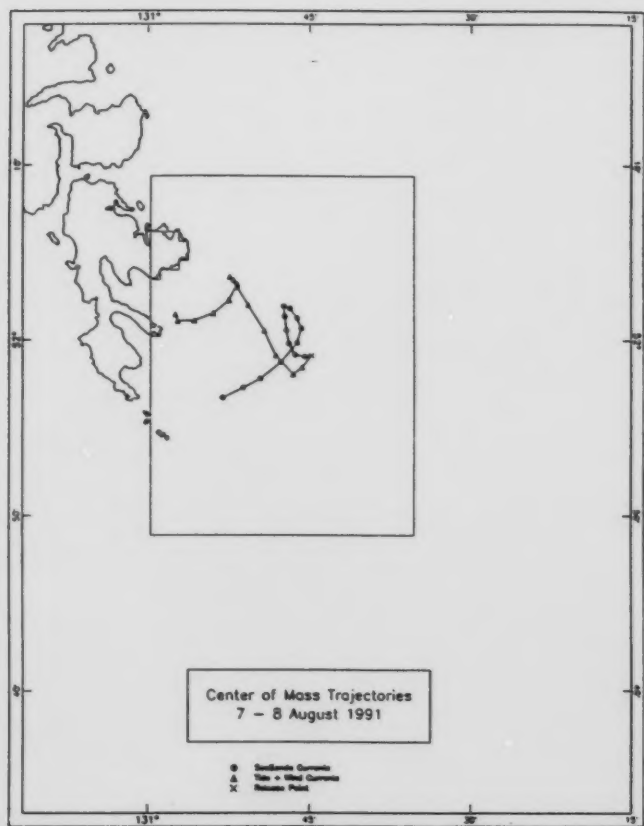


Figure 6 Comparison of centre of mass trajectories for the continuous spill with on-shore winds.

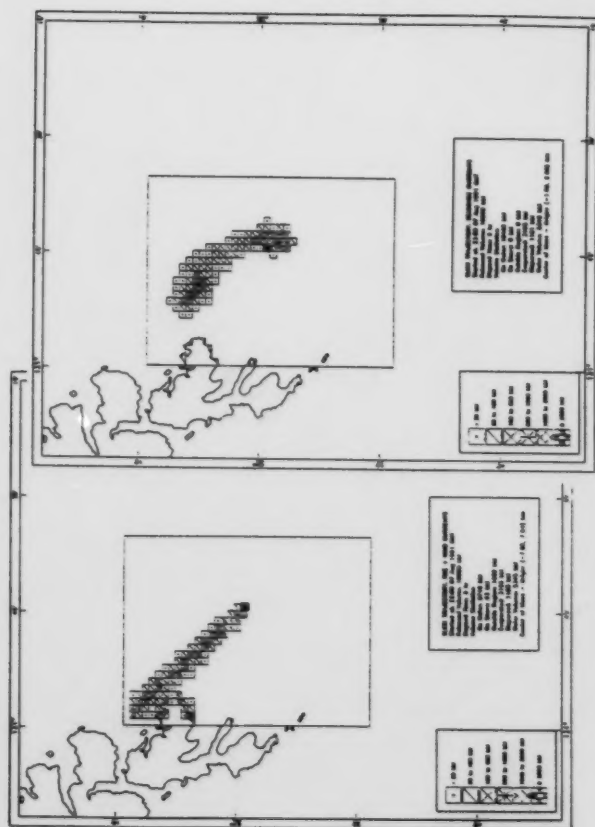


Figure 7 Comparison of the 9-h oil slick position and area for the continuous spill with on-shore winds.

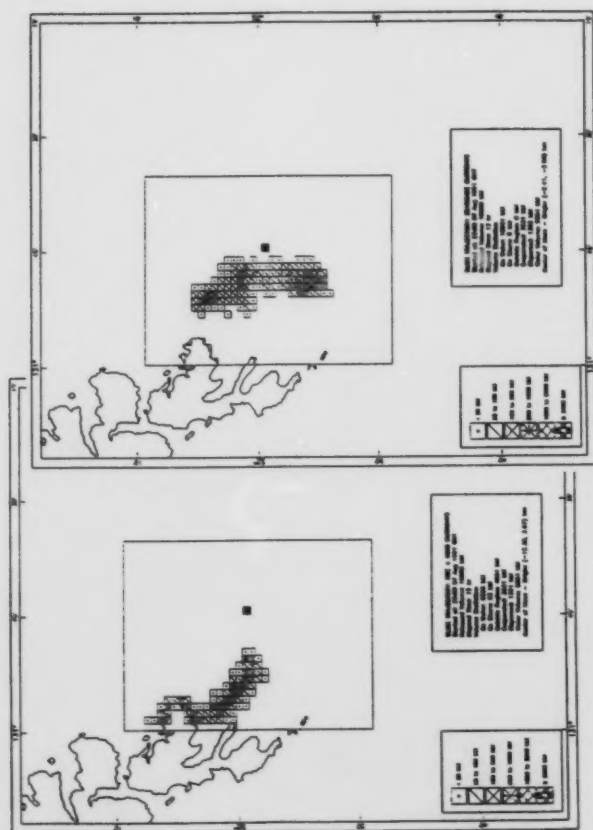


Figure 8 Comparison of the 12-h oil slick position and area for the continuous spill with on-shore winds.

The swept areas are 253 km² for tide+wind versus 337 km² for SeaSonde, but the more significant differences lies in the degree of shoreline oiling predicted with each set of forcing data.

3.2 Offshore Winds with Moderate Tides

Winds during the second simulation period were persistent from the northwest, typical of conditions during the summer. A comparison of the tide+wind current with the SeaSonde current is shown in Fig. 9. In this case the tidal signal is evident in both components and is correlated; however, the character of the signals differs. This is most notable in the u-component: the tide+wind current is directed eastward, whereas the SeaSonde u-component is mainly westward, and the difference is a consequence of the addition of the wind-driven current in tide+wind simulation using the simple 3.5% rule.

The centre of mass trajectories for each instantaneous spill simulation (Fig. 10) are consistent with the current time-series. For the tide+wind input, the oil moves downwind, reaching the model boundary in 12 h, whereupon it is lost from the calculation. The SeaSonde simulation shows that the oil moves south-southwest. The oil swaths are plotted in Fig. 11, showing that the SeaSonde currents produce much greater coverage (259 km² versus 127 km²) and indicate that the oil will remain within the modelled area considerably longer, 39 h compared with 12 h for the tide+wind conditions. Moreover, the SeaSonde results imply considerable shoreline oiling versus none for the tide+wind simulation.

The currents for both simulations 2 h following release are shown in Fig. 12 and the slick positions that result from these and similar flows over the first 4 h are mapped in Fig. 13. The SeaSonde current speeds, near the spill point, are weak despite the winds, and flowing southward around the point. In contrast, the tide+wind flows are stronger to the southeast. The slick area is similar in each case at 4 h; however, the SeaSonde current result in much less displacement. The slick positions at 8 h also show much greater displacement downwind.

The results for the 10-h continuous release are similar to the instantaneous release in these simulations.

The differences in simulations are attributable to the effects of the simple wind-driven current model in the tide+wind case, compared with the actual, topographically modified flow fields measured with the SeaSonde. For these oceanographic conditions—winds blowing off the land in an area of complex geography—simple models that add tide and wind together will not provide adequate oilspill motion predictions.

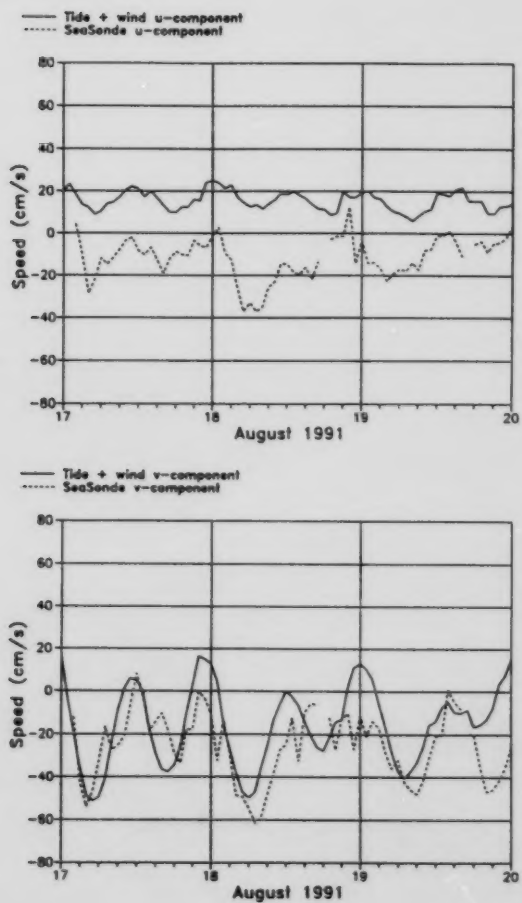


Figure 9

SeaSonde versus tide+wind currents for the offshore wind conditions.

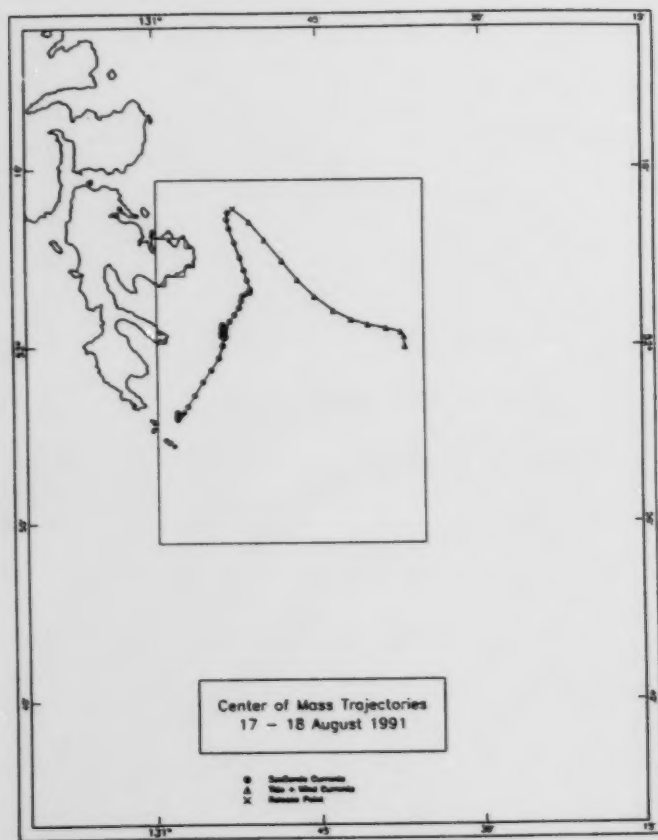


Figure 10 Comparison of centre of mass trajectories for the instantaneous spill with offshore winds.

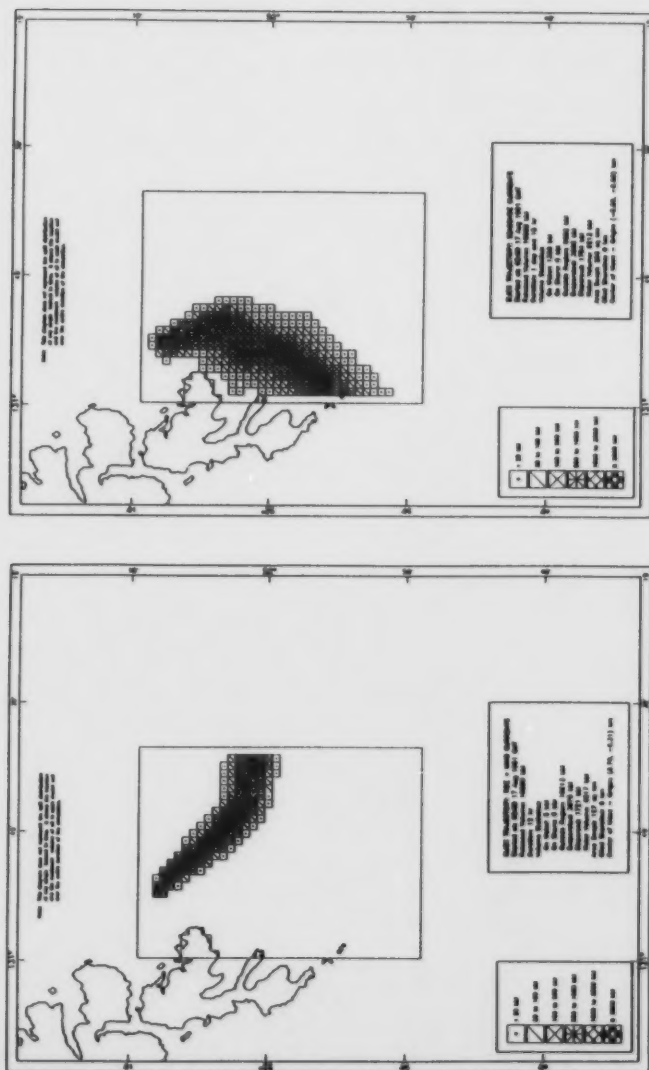


Figure 11 Oilspill swaths for the instantaneous spill with on-shore winds: tide + wind (left) and SeaSonde (right).

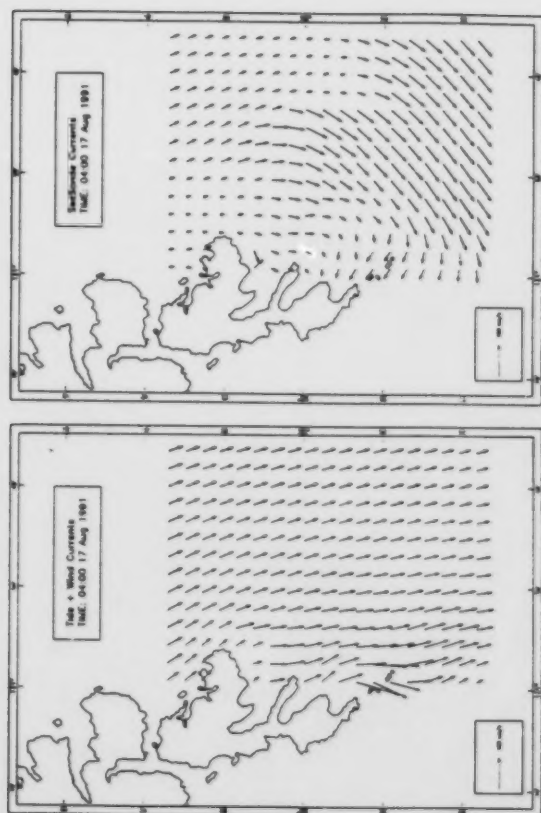


Figure 12 Comparison of currents 2 h after release for the offshore wind conditions.

3.3 Parameter Comparisons

The centre of mass trajectories provide a measure of the displacement of the slick from the release location. These displacements are plotted in Fig. 14 for the on-shore and off-shore wind conditions as functions of time. In the on-shore simulations, the rate of drift is similar for the first 5 to 8 h depending on the release history, after which point the two diverge as the trajectories move in different directions and speeds. In the case of off-shore winds, the rate of movement is consistently greater for the tide+wind current input, and the slicks move away from the spill location at speeds differing by a factor of about two. As noted earlier, the drift directions diverge from each other by approximately 50°.

The separation of the trajectories is plotted in Fig. 15 as a function of drift time. These results show that the distance between slick centres increases uniformly under both wind conditions. As expected from these simulations, the separations are greatest for the off-shore winds, reaching 10 to 18 km after 12 h.

4.0 CONCLUSIONS

Comparison of differences in slick motion using a comprehensive trajectory-fate oilspill model forced with actual currents measured with the SeaSonde versus the tide plus wind drift input shows that errors arising from the less accurate current fields were large. Most significant was the inability to correctly predict the location and timing of shoreline contact, and the rate of slick drift. Both aspects are critical in a tactical situation requiring deployment of personnel and resources.

It should also be recognized that the tidal model used for the simplified input is by no means crude, and represents a better estimate of ocean currents than would be available in many other areas of Canada. The biggest limitation in this case arose from the vector addition of the wind-driven current to the tidal flow in an area of such complex geography.

In the absence of actual oilspill data on slick motion, spreading and volume changes, it is reasonable to assume that the SPILLSIM model forced with SeaSonde currents will provide realistic forecasts of the overall features of a spill for the first few days following release. The conclusions from this analysis are:

- near the coast, where the landforms modify both wind and the ocean response, simple current models that vectorially add tidal and wind-driven components together will not provide accurate trajectory calculations;
- the nature of oil slick prediction errors arising from the simple current input include speed and direction of drift, and area of ocean swept by oil;

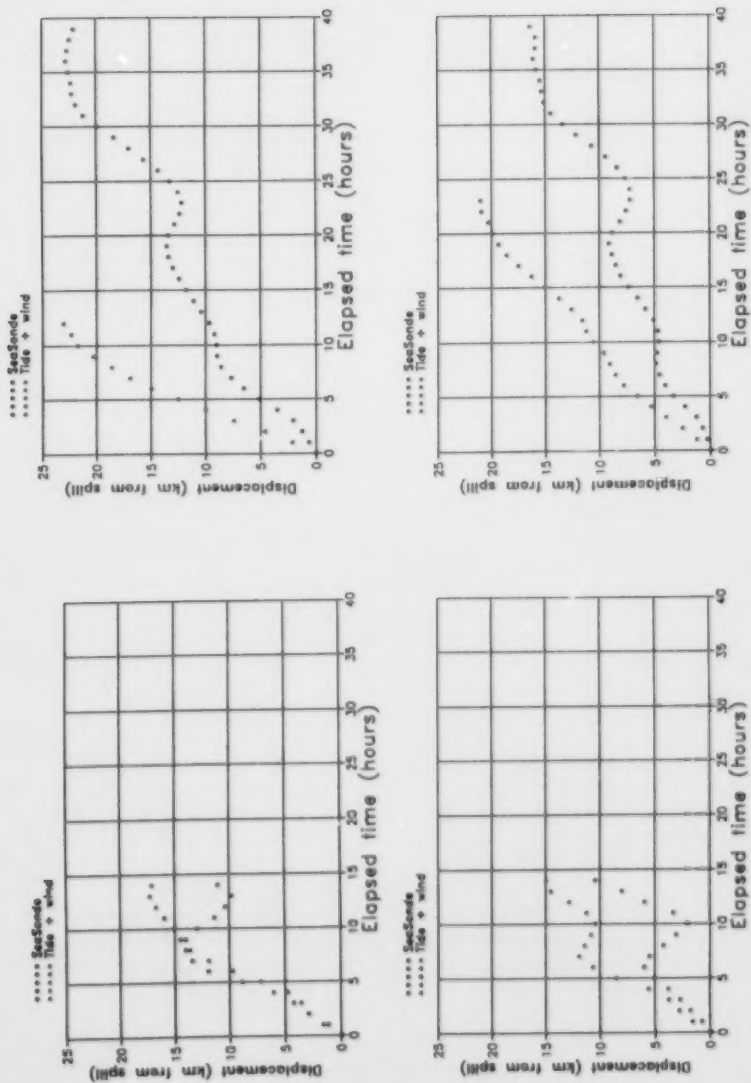


Figure 14 Centre of mass displacement versus time for on-shore winds (left) and offshore winds (right). Instantaneous releases are shown in the upper panels; continuous releases in the lower panels.

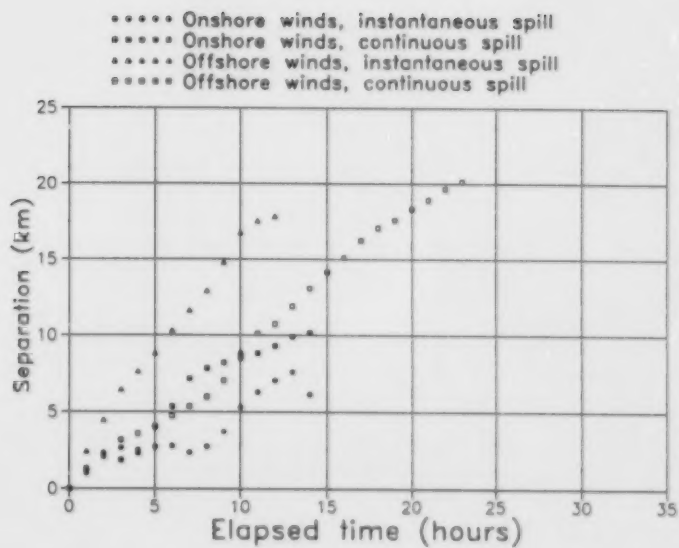


Figure 15 Centre of mass separation distance versus time.

- the consequences of these prediction errors include serious misinterpretations of the tendency for oil to come onshore, and the timing, position and extent of shoreline fouling if the oil does tend toward land;
- remotely sensed surface currents using HF radar offer a significant improvement in forecasting spill motion in real-time;
- the SeaSonde HF radar system provides an accurate, cost-effective means of building databases for spill modelling for contingency planning, or for emergency response in the absence of real-time data.

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OIL SPILL REMOTE SENSING SENSORS AND AIRCRAFT

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INTRODUCTION

Remote sensing is an important part of oil spill countermeasures and is increasing in importance. Public expectations with respect to the environment are increasing. The public expects that the government or the spiller know the location and extent of the contamination. It is also being recognized by spill cleanup personnel that remote sensing can be used to increase spill cleanup efficiency. Furthermore, the advance in electronics has made the instrumentation much cheaper and capable

The definition of remote sensing implies that a sensor, other than the eye, is used to detect the target of interest at a distance. The most common form of remote sensing as applied to oil spills is aerial remote sensing - that is using aircraft as a platform. Visual observation - irrespective of the platform used, is by definition, not remote sensing.

Remote sensing does however, include the use of satellites. This technology will be briefly reviewed in this article along with aircraft-mounted remote sensors.

OPTICAL TECHNIQUES

Optical techniques are the most common means of remote sensing. Cameras, both still and television, are particularly common because of their low price. Aerial mapping is very common and many companies are equipped with aircraft and cameras to perform this function. Many cameras have been commercially available over the past 10 years.^{1,2}

Oil has an increased surface reflectance above that of water in the visible, but also shows limited non-specific absorption tendencies. The visible spectrum is from approximately 400 to 700 nm (blue to red). Oil has several manifestations throughout the spectrum. Heavy oil appears brown, showing up in the 600 to 700 nm region. Mousse shows up in the red-brown or closer to 700 nm. Sheen shows up silvery and reflects light over a wide spectral region up to the blue. There is no strong information in the visible region from 500 to 600 nm, so often this region is filtered out, to give stronger contrast. Experimenters have found that one technique for giving high contrast to visible imagery is to set the camera at the Brewster angle (53 degrees from vertical) and use a horizontally-aligned polarizing filter which passes only that light reflected from the water surface. It is this component that contains the information on surface oil.¹ This technique is said to increase contrast by as much as 100%. Filters that have band-pass below 450 nm also may be used to improve contrast.

The use of visible techniques is largely restricted to that of documentation because the lack of a positive oil detection mechanism. Furthermore, many interferences exist. Sun glint and wind sheens can be mistaken for oil sheens. Biogenic material such as surface weeds or sunken kelp beds can be mistaken for oil.

Oil on shorelines is difficult to identify positively because weeds can have similar appearance and oil on darker shorelines cannot be detected.

Television cameras are often used. Several systems use filters to improve the contrast, in a manner similar to that noted for the photographic cameras. In the 1970's, when electronics were not highly developed, low-light level television (L³TV) was used as an inexpensive remote sensor. The advent of charge-coupled device (CCD) detectors in television with their high sensitivity, made the old generation of low-light-level televisions obsolescent. An ordinary home video camera has similar sensitivity to the former specially-purchased L³TV. New light-enhancement technology permits television to operate even in darkness. Filters are sometimes used with television cameras to enhance their utility for oil spill remote sensing, but this technique has limited success, because of poor contrast and lack of positive discrimination.

Another visible technique that has not been pursued in recent years is that of laser-illuminated television or active-gated television. The USCG had developed a prototype for their "Aireye" system. The purpose of the unit was to capture pictures of a ship's name. A laser pulse is used to illuminate the field of view and the television is gated to the pulsed laser. Unfortunately, a fully-functional unit was not completed.

Scanners are frequently used as sensors in the visible region of the spectrum. A rotating mirror or prism sweeps the field of view and directs the light to a detector. Before the advent of CCD detectors this method provided much more selectivity and sensitivity than a television camera. The other advantage of using scanners is that signals are digitized and can be processed before display. In recent years, technology has evolved and similar digitization can be achieved without scanning by using a CCD imager and continually recording all elements, each of which is directed to a different field of view on the ground. This type of sensor is known as a push-broom scanner. The advantages of this technology over the older scanning types are many. Several types of aberrations and errors can be overcome, units are more reliable than mechanical ones, and all data are collected simultaneously for a given line perpendicular to the direction of flight. In Canada, development on the MEIS (Multi-spectral Electro-optical Imaging Scanner) devices has taken place in the past few years. This series of push broom devices feature relatively narrow band widths and high resolutions. MEIS II has 1024 detector elements, and MEIS FM, currently under development, has 6000 elements, giving it near-photographic quality.

In summary, use of the visible spectrum for oil detection is limited, it does, however, offer economical means of documenting spills and means of providing baseline data on shorelines or relative positions.

INFRARED SENSORS

Oil which is "optically-thick" absorbs solar radiation and re-emits this radiation as thermal energy largely in the 8 to 14 micron (8000 to 14000 nm) region. This phenomenon lends itself to oil detection by infrared sensing. This oil appears to be cool in the infrared (compared to the surrounding water). Thin oil or sheens are not detected by infrared. In summary, thick oil appears hot or white in infrared data, intermediate thicknesses appear cool and black, and thin oil is not detectable. The thicknesses at which these transitions occur are not known, but scientific evidence indicates that the transition between the heated and cooled layer lies between 50 and 150 microns and the minimum detectable layer lies between 10 and 70 microns.^{3,4,5,6,7} The reason for the appearance of the "cool" slick is not fully

understood. One theory is that the evaporative cooling of the slick exceeds its radiative heating at a certain thickness and thus appears cool compared to the water. Another and more likely theory, is that a moderately thin layer of oil on the water surface causes destructive interference of the thermal radiation waves emitted by the water, or in some other way attenuates this signal, thereby reducing the amount of thermal radiation waves emitted by the water.¹

Infrared cameras are now very common and several commercial units are available. In past years scanners with infrared detectors were largely used. Infrared detectors of any type suffer from the disadvantage that their detectors require cooling to avoid thermal noise, which would destroy any useful signal. The traditional method of cooling the detector was by liquid nitrogen. This generally gives about 4 hours of service. New, smaller sensors can use electric thermal coolers or Joule-Thompson coolers which use the cooling effect realized when a gas is expanded. This type of cooling implies that a gas cylinder or compressor be transported with the sensor but refills or servicing may not be required for days at a time.⁸

Most infrared sensing takes place at what is known as the thermal infrared at the wavelengths 8 to 14 microns. One sensor which is designed as a fixed-mounted unit uses the differential reflectance of oil and water at 2.5 and 3.1 microns.⁹

The relative thickness information in the infrared is useful because it can be used to direct countermeasures equipment to thicker portions of the slick. Oil detection in the infrared is not positive, because several false targets can interfere - including weeds, shoreline, and oceanic fronts. Infrared is, however, somewhat economical and is currently the prime tool used by the spill remote sensor.

ULTRAVIOLET SENSORS

Oil slicks display high reflectivity of ultraviolet radiation even at thin layers (<0.01 microns). Ultraviolet sensors can be used to map even thin sheens of oil. Overlapped ultraviolet and infrared images are often used to provide a relative thickness map of spills. Ultraviolet cameras, although inexpensive, are not used to a great extent because it is difficult to overlay camera images.⁴ Scanner data and push-broom scanners allow for the easy superimposition of data and the production of IR/UV overlay maps. Ultraviolet data is also subject to many interferences or false images such as wind slicks, sun glints, and biogenic material. Because these interferences are often different than those for infrared sensing, the combination of IR and UV can provide a more positive indication of oil than the use of either technique alone.

FLUOROSENSORS

Fluorosensors employ the property that some compounds in the oil absorb ultra-violet light and re-emit part of this energy in the visible. Since very few other compounds show this tendency, fluorescence is a strong indication of oil presence. Natural fluorescing substances such as chlorophyll, fluoresce at sufficiently different wavelengths to avoid confusion. There is, however, a strong natural fluorescent material known as "gelbstoff" which consists of a broad spectrum of fluorescing materials. This background changes very slowly along the sensor path and thus can be compensated for rather easily. Different types of oil yield a slightly different fluorescent response. It is possible to differentiate between heavy and light oil under ideal conditions. This property is currently useful only as a scientific tool. Figures 9 and 10 show signals from older instruments.

Most laser fluorosensors employ a laser operating in the ultraviolet region

between 340 and 300 nm.^{1,10} With this wavelength of activation, there exists a broad organic matter fluorescent return, centred at 420 nm. This is the Gelbstoff or yellow matter, which can be easily annulled. Chlorophyll yields a sharp peak at 685 nm. Oil fluorescent return is in the region between 400 to 550 nm with peak centres in the 480 nm region. There also exists a phenomenon known as Raman Scattering, which involves molecular reaction between the incident light and the water molecules on the surface. The water molecules can absorb some of the energy as rotational-vibrational energy and return the light as the incident energy less this energy of rotation or vibration. The water Raman signal occurs at 344 nm when the incident wavelength is 308 nm. The water Raman is useful for maintaining calibration of the fluorosensor in operation, but had also been used in a limited way to estimate oil thickness, because oil on the surface will suppress the water Raman signal in proportion to thickness.¹¹ The point at which the Raman signal is entirely suppressed is not known, and each oil type has a different absorption parameter. Therefore it is difficult to employ water Raman suppression as a thickness sensor.

It is also possible to use the principle of oil fluorescence on a small scale. Work has been done to develop the use of a hand-held UV light to detect oil spills at night at short range.¹²

Another related instrument is the "Fraunhofer Line Discriminator" which is essentially a passive fluorosensor using solar irradiance instead of laser light.¹ This instrument did not attain great success because of the limited discrimination and the poor signal-to-noise ratio. Laser fluorosensors are thought to have significant potential for the future because they may be the only means to discriminate between oiled and un-oiled weeds and detecting oil on a variety of beach types. Additionally, the sensor offers the only means of detecting oil in certain ice and snow situations.

MICROWAVE AND RADAR RADAR

Oil on a sea surface damps some of the small capillary waves. Since these capillary waves reflect radar energy producing a "bright" image known as sea clutter, the presence of an oil slick can be detected as a "cold" sea or one which has an absence of this sea clutter. Unfortunately oil slicks are not the only phenomenon which is detected in similar manner. Interferences are many and include fresh water slicks, wind slicks (calms), wave shadows behind land or structures, weed beds which calm the water just above them, glacial flour, biogenic oils, whale and fish sperm. Because of the number of these interferences, radar can be useless in situations such as in Prince William Sound where the dozens of islands, fresh water inflows, ice, and other features yield literally hundreds of false targets. Radar is, despite these limitations, an important tool for oil spill remote sensing because it is the only useful sensor for large area searches, as will be demonstrated later, and because it is one of the few sensors that can "see" at night and through clouds or fog.

The usefulness of radars in conducting large-area searches is illustrated in Table 1. If one compares different sensor options in searching for lost-cargo-type spills. The scenarios given are real. A ship will upon rare occasions, reach its destination or a point in its journey and the crew discovers that it has lost part of its cargo. A similar situation existed with the KURDISTAN tanker which broke in half, but due to the differential drift between the ship halves and the oil, the location of the

lost cargo was unknown until found by remote sensing techniques. The PETER STUYVESANT incident is a classical case of lost cargo. The vessel was loaded at Valdez with crude and upon arrival at the Straits of Juan De Fuca found that some of its tanks were empty. A similar situation existed for a vessel over the entire run from Lancaster Sound to near Newfoundland. Table 1 illustrates that the only practical means of searching for this cargo is to use a wide-range radar and a jet airplane. Use of limited-range radars is not a practical means for performing this function.

Table 1 Times to Cover Search Area Entirely For Three Historic Situations
Aircraft and Sensors Time in Days to Cover Area

Strait	KURDISTAN	PETER STUYVESANT	Dair
Propeller and UV/IR	2	60	110
Propeller and sm. radar	1	23	42
Jet and small radar	1/5	5	8
Jet and SAR radar	1/20	1	1

Two basic types of radars have application to oil spills and general environmental remote sensing, SARs or synthetic aperture radars and SLARs or Side-Looking Airborne radars. The latter is an older technology, but cheaper, and employ long antennae to try to improve spatial resolution. The synthetic aperture radars use the forward motion of the airplane to synthesize a very long antenna, thereby achieving very good spatial resolution (which is range independent) at the expense of sophisticated electronic processing. SARs are more costly, but are capable of much more range and much greater resolution than SLARs.

Experimental work on oil spills has shown that X-band radar yields better data than L or C band radar. In addition, it has been shown that antenna polarizations of vertical for transmission and vertical for reception (VV) also yield better results than other configurations.^{1,13,14} Radars are thought to be limited by sea state, too low sea states will not produce sufficient sea clutter in the surrounding sea to contrast to the oil and very high seas will scatter radar sufficiently to block detection inside the troughs. Detailed work on sea state limits has not been done but cases of both extremes have been documented in the literature.^{1,15}

Search radars such as frequently employed by the military have little - if any - application to oil spills because they frequently remove the clutter signal. Thus, the primary signal of interest is deleted. Furthermore these radars have signal processing optimized to pinpoint small, hard (to radar signals) objects such as periscopes. This signal processing is very detrimental to oil spill detection.

Ship radars suffer from similar limitations and have the additional limitation of low altitude that restricts their theoretical range to between 8 to 30 km., depending on antenna height. Ship radars can be adjusted to decrease the effect of sea clutter de-enhancement. Ship-borne radars were successfully used at 8 km. to detect a surface slick in the Baltic and during a trial offshore Canada at a maximum range of

17 km.¹⁶ The technique is highly limited by sea state and, in all cases where it was used, the presence and location of the slick was already known.

In summary, radars optimized for oil spills can provide useful application to spill remote sensing, in particular for large area searches and for night-time or foul weather work.

MICROWAVE SCATTEROMETERS

A microwave scatterometer is a device that measures the scattering of microwave or radar waves by the target surface. The presence of oil reduces the scattering of the radar signals just as it does for the radar sensors and therefore suffers the large number of interfering factors noted above. One radar scatterometer was flown over several slicks and employed a low-power transmitter operating in the Ku band (13.3 Ghz).¹ The advantage of this type of sensor is that it has a similar aerial coverage to optical sensors and has a nadir aspect (looks straight down). The disadvantages of the sensor include the lack of discrimination for oil and the lack of imaging capability.

MICROWAVE RADIOMETERS

The ocean is an emitter of microwave radiation. Oil on the ocean is a strong emitter of microwave radiation compared to water and thus appears as a bright object on a darker sea. Water has an emissivity factor of 0.4 compared to oil of 0.8.¹ A passive device can detect this emission and could provide a detection means for oil. Furthermore there is a signal change with thickness and, in theory, the device could measure thickness. This detection method has been tried over the years, but generally has not resulted in great success. First, the methodology depends on knowing many environmental and oil specific parameters and second, the signal return is dependant on signal strength but in a cyclical fashion.³ A given signal strength can imply any one of two or three signal film thicknesses within a given slick. Emission of microwaves is a maximum when the effective thickness equals an odd multiple of a quarter wavelength of the observed energy. The method suffers from other weaknesses as well. Biogenic materials also interfere and the signal-to-noise ratio is poor. The methodology does not appear to work at all on water-in-oil emulsions.³ Scanning radiometers are necessary to produce a thickness map, but scanning with this device is difficult. The Swedish Space agency has done some work with different systems, primarily a dual band, 22.4 and 31 Ghz, device, also with a single band 37 GHz device.¹⁷ Tests of the devices have achieved only mixed results. TRW, a firm in southern California has demonstrated the use of a passive microwave during the AMERICAN TRADER spill off Huntington Beach. In summary, passive microwave radiometry may offer potential as a useful oil sensor. Its potential as a reliable slick thickness measurement device still needs to be established.

SLICK THICKNESS SENSORS

There exists a need to measure oil spill thickness. First, no reliable methods exists and the basic physics of oil spreading and behaviour are not well understood. The ability to measure slick thicknesses would, no doubt, result in significant advances in the understanding of spill behaviour and effects, and improve our ability to deal with them. There does not exist a reliable laboratory method to measure thin slicks at this time. Second, there is strong motivation to develop a slick thickness sensor so that the effectiveness of certain countermeasures such as dispersants can be measured. The volume of oil remaining on the water cannot be measured without such a device.¹⁸ Finally, there is strong motivation to determine the amount of oil in fugitive slicks. Aircraft surveillance of slicks often results in erroneous oil quantity estimates. The variances of measuring slick thickness using a combination of sensor data and visual estimates, is illustrated in Table 2. This table contains the results of a field trial (named NIFO after a Norwegian organization) to assess oil slick volume using existing aerial techniques.

TABLE 2		RESULTS OF THE NIFO TRIALS				
Product	Quantity	Country Airplane - Amount Reported				
spilled	(cu. metres)	Germany	UK	Norway	Holland	Sweden
Marine Fuel	1	1	0.25	12	0.1	1
Crude	5	4	0.2	15	0.04	8.1
Mousse	2.1	2	-	7	0.02	1.6
Drilling Fluid	5	-	-	-	-	-
Diesel Fuel	1	1	-	-	-	-
Condensate	0.02	2	-	-	0.05	-
SENSORS ON		SLAR	SLAR	IR/UV	SLAR	SLAR
BOARD		IR/UV	IR/UV		IR/UV	IR/UV
MWR = microwave radiometer		MWR				MWR

The use of the suppression of the water fluorescence Raman peak in laser fluorosensor data discussed above has not been exploited or tested fully.¹¹ This technique may work for thin slicks, but probably not for thick ones. Attempts to calibrate the thickness appearance of infrared imagery have been made, but also have not been successful.^{5,6} It is suspected that the temperatures of the slick as seen in the IR are highly dependent on oil type, sun angle and weather conditions. If this is the

case, it is not possible to use IR as a calibrated thickness measurement tool. Accurate surface methods do not exist, therefore the calibration of existing equipment is very difficult.¹⁹ The use of sorbent techniques to measure surface thickness yields highly variable results.¹⁸ As noted in the discussion of the microwave radiometers above, the signal strength as measured by these instruments can imply one of several thicknesses. This methodology does not appear to hold promise for reliable oil thickness measurements.

A variety of electric, optical and acoustic techniques were investigated to measure oil thickness.²⁰ Two promising techniques were pursued in a series of laboratory measurements. The first technique is known as "thermal mapping".²¹ A laser is used to heat a region of oil and the temperature profiles created over a small region near this heating is examined using an infrared camera. The temperature profiles created are dependant on the thickness. An even more promising technique is a "laser acoustic" one.²² An infrared carbon dioxide laser is used to heat the oil layer. This sets up thermal and acoustic waves in the oil. The acoustic waves can be detected using another laser and an interferometer. The thickness can be determined from the time of propagation of the acoustic wave between the upper and lower surfaces of the oil slick. This is a very reliable means of studying oil thickness and offers great potential. A consortium of agencies including Esso Resources Canada, Environment Canada, the United States Minerals Management Service, and the American Petroleum Institute is pursuing the technology. Laboratory tests have confirmed the viability of the method and a test unit will be flown in the near future to confirm the operability of the concept.

REMOTE SENSING OF OIL UNDER DIFFICULT CIRCUMSTANCES OIL-IN-WATER

The only instrument capable of remotely measuring oil in the water is the laser fluorosensor. One instrument, the Fluoroscanner, was built specifically for this application. The system operates in a similar manner to that of a normal fluorosensor, except that only that signal derived from fluorescence in the water column is analyzed. The depth of penetration is thought to be a maximum of 6 metres. Because of the attenuation of the water column, sensitivity decreases logarithmically downwards from the water surface.

Another instrument that holds potential for detecting neutrally-buoyant oil is the Lidar bathymeter. This instrument uses a laser in the green region to map bottom contours. Presence of massive amounts of oil floating beneath the surface would, in theory, be detected.

OIL-ON-ICE

Oil has been detected on ice using visible techniques.¹ Oil appears to be black or brown against the white background of the ice. Sediment also has the same appearance and constitutes the major interference. Microwave techniques have been tried but were not successful because of the strong emissivity of the ice.¹⁴ Microwave radiometry is, however, very useful in discriminating between first and multi-year ice. The best potential for positively identifying oil on ice resides in the laser fluorosensor.

OIL IN OR UNDER-ICE

Extensive work was done in this area by Esso Resources and Environment Canada. Examination of non-contact techniques such as the use of radar showed that this technique did not have potential.²³

A contact technique using acoustic means to detect the oil was developed to the prototype testing stage.^{24,25} The technique uses the phenomenon that oil appears to be a solid to a sound wave. Liquids propagate shear and pressure waves (two different types of sound waves) in different ways. By examining the ratio of shear and pressure waves, one can find out if oil is present in or under the ice and even at what depth. The methodology requires further testing and development before proceeding to commercialization.

OIL-AMONGST-ICE

Oil amongst ice has been detected and mapped by both UV and IR techniques, however its location was already known.¹ This technique will work for situations where there is much oil and a large amount of open water. In most situations, the best potential for detection is offered by the laser fluorosensor.

REAL TIME DISPLAYS AND PRINTERS

A very important aspect of remote sensing is the production of data so that operations people can quickly and directly use it. Real time displays are very important so that the remote sensor operators can adjust instruments directly in flight and so that they can provide information quickly on the location or state of the spill.

In 1980, the Canada Centre for Remote Sensing, with support from Environment Canada, developed the first generic real-time display (generic = compatibility with different sensors). The unit, known as the Norpak, provided a good deal of service displaying multispectral, IR and UV data. A series of devices under the trademark, ALICE, have been built by Knudsen Engineering. These devices are also used to display electro-optical data. A new device built by the same firm will allow the display of radar data along with optical data.

No printing devices are commercially-available for electro-optical data. Development work is required. Nine-inch strip-map hardcopy and digital video imagery is available from most imaging radar sensors.

SATELLITE REMOTE SENSING

The use of satellite remote sensing for oil spills has been attempted several times. The slick from the IXTOC I well blowout in Mexico was detected using GOES and also by the AVHRR (Advanced Very High Resolution Radiometer) on the LANDSAT satellite.¹ Subsequently a blowout in the Persian Gulf was detected. The massive EXXON VALDEZ slick was detected on SPOT satellite data. Oiled ice in Gabarus Bay resulting from the KURDISTAN spill was detected using LANDSAT data.^{26,27} It is significant to note that in all these cases the position of the oil was known and in all cases, data had to be processed to see the oil. Data processing always lasted several weeks.

Table 3 SURVEY OF SENSOR USE AND ASSESSMENT

SENSOR SATELLITE	AUTHORS)	REF. LOCATION/TEST	FINDINGS	ADVANTAGES	DISADVANTAGES
FLUORESCENCE	AVHRR	29	61 Gulf oil spill	remote, fast cost	not entire disk, low contrast
	AVHRR	30	60 Exxon Valdez	large scale coverage	poor resolution
	LANDSAT-TM	30	60 Exxon Valdez	large scale coverage	poor resolution
	LANDSAT-TM	36	60 EXXON VALDES Spill	all could be detected	poor coverage
	SPOT-PS	30	60 Exxon Valdez	all could only be detected if known	poor resolution
	SPOT-PS	36	60 EXXON VALDES Spill	all could only be detected if known	poor coverage and discrimination
OPTICAL - VIS	Oldenburg	10	60 Marpol Ex.	oil type	fluctuates known with weathering
	Oldenburg	32	60 Marpol Ex.	oil type, some thickness indication	changes with weathering
OPTICAL - IR	scanner	31	60 Italy survey	good coverage	poor discrimination
	scanner	47	60-87 North Sea 23 slicks	more positive than radar	limited spatial coverage
	scanner	35	83-86 Baltic Sea	some indication of thickness	
OPTICAL - VIS/IR	FLIR	31	60 Italy survey	movement useful	poor discrimination than passive
	BAS camera	8	87 disp. field trial	very clear image	unaffected areas uncertainty
	BAS camera	36	60 EXXON VALDES Spill	cheap, fast to install	does not discriminate oil in waste
	video camera	37	88-90 Various shorelines	cheap, portable	location needs confirmation
MICROWAVE	SLAR	33	86 Archimedes II - North	day/night and all weather	false signals, classification needed
	SLAR	34	86 North Sea	day/night and all weather capability	only for large slicks (8 km) slicks
	SLAR	47	86-87 North Sea 34 slicks	day/night and all weather capability	false signals especially near rig
	SLAR	35	83-86 Baltic Sea	long range, good spatial coverage	false signals
	SLAR	36	60 EXXON VALDES Spill	many false images in FWS area	false signals from cliffs, glacier runoff
	1 channel	35	83-86 Baltic Sea	preliminary indications of usefulness	

There are several problems in reliance on satellite remote sensing. The first is the frequency with which overpasses occur.²⁸ The second is the absolute reliance on clear skies to perform optical work. These two factors combined can give a very low probability of seeing a spill on satellite data. The case of the EXXON VALDEZ spill illustrates this well.³⁰ Although vast amounts of ocean were covered by the spill for over a month, only one clear day and a satellite overpass occurred, that on April 7. The third disadvantage of satellite remote sensing is the difficulty in developing algorithms to highlight the oil slicks and the long time to do so. It took over two months in the case of the EXXON VALDEZ spill before the first group managed to "see" the oil slick in the satellite imagery, although its location was precisely known.

Optical satellite imagery does not offer much potential for oil spill remote sensing. The new European and Canadian radar satellites may offer some potential for large offshore spills, however limited testing with the European satellite, ERS-1 has shown that many false signals are present in most scenes.

SUMMARY RECOMMENDATIONS

A review of tests conducted by several agencies was compiled and is given in Table 3. This review and the above technological assessment form the basis for a series of recommendations.

The first sensor recommended for oil spill work is an infrared camera. This is the cheapest and most applicable device. A camera and ancillary equipment can be purchased for under \$100,000 and weighs less than 50 kg. This is the only piece of equipment that can be purchased off-the-shelf. All other sensors require special order and often, actual development. The second sensor recommended is an UV and visible device. These devices vary a good deal in price, size and state of development. The laser fluorosensor offers the only potential for discriminating between oiled and un-oiled weeds or shoreline, and for positively identifying oil pollution on ice, amongst ice and in a variety of other situations. This instrument however is large and expensive. A production unit could cost \$500,000 and weigh 200 kg. Radar, although low in priority for purchase, offers the only potential for large area searches and foul weather remote sensing. SAR is recommended and a unit will cost about \$2,000,000 to \$4,000,000 and will require a dedicated aircraft. Most other sensors are experimental or do not offer good potential for oil detection or mapping. Any sensors package should include a real-time printer and display.

REVIEW OF AIRCRAFT AND AIRCRAFT MODIFICATIONS

A review of aircraft and aircraft modifications was commissioned by Environment Canada.⁴⁸ The purpose of the review was to make available data on modifications necessary for mounting oil spill remote sensing. Aircraft modifications are very costly to design. Using existing designs or kits can save the high cost of design, cost which can rise as high as millions of dollars.

Table 4 shows the installation of camera ports in commercial aircraft.

AIRCRAFT INSTALLATIONS OF CAMERA PORTS

Table 4	SECOND-PARTY INSTALLER				MANUFACTURER
AIRCRAFT	DOWNTOWN AIRPARK	AVCON	SERVI-CENTRE	AAR-OK	AVAILABLE
BEECH KING AIR	X	X			
BEECH SUPER KING AIR	X	X		X	
CESSNA CARAVAN			X		
CESSNA CITATION		X			X
CESSNA CONQUEST		X		X	
FAIRCHILD SA226-T	X				
LEAR JET		X			X
TURBO-COMMANDER	X				
TWIN OTTER					X

A Survey of aircraft containing radars was also completed. The survey results are shown in Table 5.

RADAR INSTALLATIONS			
Table 5			
COMPANY	AIRCRAFT	SAR	SLAR
INTERA	CHALLENGER	MDA/Litton	
INTERA	CESSNA CONQUEST	MDA/ERIM	
CCRS	CONVAIR 580	MDA/CAL	
U.S. NAVY	LOCKHEED P3A	ERIM	
UNIDENTIFIED	BAE-125-800	MDA	
UNIDENTIFIED	FALCON 50	MDA	
UNIDENTIFIED	KING AIR 300/350	MDA	
ERIM	CONVAIR 580	ERIM	
ERIM	CONVAIR 580	ERIM	
AVCON	LEARJET		LORAL
ENVIRONMENT CANADA	DASH 7		CAL
BERCHA	FAIRCHILD MERLIN IV		MOTOROLA
U.S. COAST GUARD	FALCON 20		MOTOROLA
U.S. COAST GUARD	FALCON 20		MOTOROLA
U.S. COAST GUARD	LOCKHEED C-130		MOTOROLA
AVCON	LEARJET 35		GOODYEAR
INTERA	CESSNA CONQUEST		TERMA

Laser fluorosensor installations (past and present) and observation windows are listed in Table 6 and Table 7, respectively.

SURVEY OF LASER FLUOROSENSORS AND AIRCRAFT

Table 6

AIRCRAFT	FLUOROSENSOR MANUFACTURER
AERO-COMMANDER	BARRINGER
BN ISLANDER	BARRINGER
DC-3	BARRINGER
DIAS F-27	BP
DIAS F-27	BP
DORNIER 228	U OF OLDENBERG

SURVEY OF OBSERVATION WINDOWS

Table 7

AIRCRAFT	WINDOW	WINDOW
	IS USED	KITS AVAILABLE
DASH 7	X	
TWIN OTTER	X	X
KING AIR	X	X
FALCON 20	X	
LOCKHEED ELECTRA	X	
LOCKHEED C-130	X	
LEARJET		X

A list of remote sensing aircraft found in the survey and from other contacts is given in Table 8. The survey is more complete for North America than other locations. The survey shows the preponderance of certain types of aircraft used for remote sensing applications.

SURVEY OF REMOTE SENSING AIRCRAFT IN NORTH AMERICA

Table 8

AIRPLANE	TOTAL NUMBER	SAR	SLAR	SCANNER	CAMERA	OBSERV. WINDOW	OTHER/ SPECIAL
CONVAIR 580	6	✓		✓	✓		✓
CESSNA CONQUEST	4	✓	✓	✓			✓
KING AIR	4			✓	✓		✓
CASA	3		✓	✓	✓		
FALCON 20	3		✓	✓	✓	✓	✓
FOKKER F-27	3						✓
LOCKHEED P3	3	✓					✓
CESSNA CARAVAN	2						✓
CESSNA CITATION	2			✓	✓		
DASH 7	2		✓		✓	✓	✓
DASH 8	2						✓
GULFSTREAM IV	2		✓				
CHALLENGER	1	✓					
DC-8	1						✓
DORNIER 228	1		✓	✓	✓		
FAIRCHILD MERLIN	1		✓	✓	✓		
SKYVAN	1						✓
TWIN OTTER	1				✓		
LOCKHEED ELECTRA	1		✓				✓

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MECHANICAL RECOVERY OF OIL IN ICE

by

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ABSTRACT

Two oil spill countermeasures projects were conducted by Counterspil Research Inc. on behalf of the Canadian Petroleum Association in 1991. In the first, a literature review was undertaken of mechanical systems used for removing oil in ice. This resulted in a compilation of recovery methods, with the most promising concepts being identified for further research. In a second study, the Foxtail rope mop skimmer was evaluated in crude, diesel oil and ice, and its performance documented.

1. REVIEW OF MECHANICAL RECOVERY SYSTEMS

BACKGROUND

Since the mid-1970s, extensive work has been directed at developing methods for removing oil in ice. Although many research programs have been conducted, few commercial devices or widely accepted approaches have resulted.

In order to identify new solutions, the Canadian Petroleum Association (CPA) undertook a systematic review of mechanical techniques for recovering oil in ice. This was part of its implementation program under the Task Force on Oil Spill Preparedness in the Upstream Petroleum Industry.

Project objectives were to:

1. Review literature on the recovery of oil in ice inclusive of R&D, conceptual, evaluation and spill incident data.
2. Catalogue the compiled information according to recovery principle, and
3. Assess the potential of each concept in the context of actual cleanup.

The study considered work conducted in Canada, the USA, Norway, Sweden, the UK, and USSR. The literature were consulted extensively and the authors' experience in testing, selecting and using skimmers drawn upon as appropriate. Collected data were then organized into a catalogue format to facilitate use of the report as a reference document:

1.0 INTRODUCTION

The study background is indicated. The most promising techniques are identified along with recommendations for future work.

- | | |
|-------------------------|--|
| 2.0 MAIN ENTRIES | Devices extensively researched, prototypes, or commercially sold units are listed according to recovery principle. Entries are in alphabetical order in each of seven categories and an Index is included. |
| 3.0 RECOVERY CONCEPTS | Ideas suggested at workshops for the recovery of oil in ice and less plausible concepts are summarized. |
| 4.0 OIL SPILL INCIDENTS | Mechanical methods used in past spills in ice are reviewed. |
| 5.0 REFERENCES | All references consulted during the study are listed including those sources which yielded limited data. |

Forty-seven MAIN ENTRIES resulted which comprise the catalogued information requested by CPA. These were ultimately compiled from test reports, catalogues and manufacturers' brochures as follows:

Background Data

- | | |
|----------------------------|---|
| <i>Operating Principle</i> | Oil recovery and ice processing mechanisms. |
| <i>Development Status</i> | The stage to which the device has been taken, i.e. prototype or commercial product. |
| <i>Specifications</i> | Primary technical specifications. |
| <i>Deployment</i> | Requirements to deploy and use the system. |

Performance Assessment

- | | |
|--------------------------------------|--|
| <i>Test Results</i> | Evaluation and actual use data. |
| <i>Oil/Ice Processing</i> | Existing capability to recover oil in various ice forms. |
| <i>Factors Affecting Performance</i> | The main parameters determining oil collection. |
| <i>Feasibility of Use</i> | Potential application of the device to oil and ice. |
| <i>Development Potential</i> | The projected outcome of further research on improving oil recovery in ice. High, medium and low designations are given. |
| <i>References/Contacts</i> | Sources of further technical information. |

The catalogued data focuses on seven groups of skimmers organized according to their oil removal principles, noted on the following page.

1. Disc/Drum Skimmers
2. Rope Mop Skimmers
3. Sorbent Belt Skimmers
4. Submerging Plane Skimmers
5. Vacuum Skimmers
6. Weir Skimmers
7. Other Concepts/Combination Skimmers

DISCUSSION OF FINDINGS

In addition to the compendium of indexed listings presented in catalogue format as 47 Main Entries, a summary of less feasible concepts was also prepared which either hold little promise for future research or have already been considered in prototype development and testing.

Of the many spill incidents reported in conference and seminar proceedings, only a limited number specifically refer to mechanical techniques utilized for oil spill cleanup in ice. These were briefly summarized and relevant comments incorporated into the Main Entries, as appropriate.

Subsequent to their compilation, the more promising methods comprising the Main Entries were further reviewed and **Low**, **Medium** and **High** designations for Development Potential examined on a relative basis:

Low	The device warrants no further consideration.
Medium	Testing and/or modification might result in an improved system.
High	Good development potential.

Results of the post-compilation analysis can be summarized as follows:

1. Skimmers studied extensively for their capability in ice include the Lockheed CleanSweep disc/drum, Marco belt and rope mop devices.
2. Of these, rope mop machines comprise the most versatile approach, largely because they can be easily deployed from vessels of opportunity in many configurations and readily positioned in oil in ice.
3. The Arcat Skimmer, which incorporates the rope mop, is well designed but could be further improved in stationary operations through the use of a single rotating brush or other system to draw oil toward the rope mop.
4. The more recently available vertical rope mop machines also warrant further development work to upgrade their performance through the use of pumps integral to the wringing mechanism, flatly configured rope mops, and guide and lead rollers which minimize inadvertent liquid losses.

5. Disc/drum skimmers now include the WP-1 Oil Retrieval System. Further research should be undertaken on this commercial device, rather than on new tank models, to determine its capability in broken ice with and without the modifications (such as paddles) investigated in past studies.
6. The Elastec Drum Skimmer should also be tested to determine optimum performance parameters in open water and broken ice. Like disc skimmers, its main advantages are ease of deployment and applicability to medium viscosity oils. Comparative tests with the Vikoma/Hoyle T-Disc Skimmer could be undertaken as well. In both cases, no developmental work on the skimmers is recommended.
7. The disc/drum concepts, however modified, are likely to continue to offer oil skimming potential in relatively low currents and calm water, with a capability to process some debris including smaller ice forms.
8. Evaluations of the three Frank Mohn Transrec skimming cassettes should be monitored. No independent development work is seen to be necessary.
9. Porous inclined planes appear to represent less potential for recovering oil in ice as compared with the other approaches.
10. Ice processors and deflectors have been developed and tested in several different formats. These have been applied to belt, weir and disc skimming systems. Generally, they can result in a more complex oil recovery system but have been shown to be capable of moving smaller ice forms to increase performance. Further research is likely to result in limited improvement to oil recovery when such systems are used.
11. The Lori brush package has potential application to relatively viscous oils. Testing of existing units should be considered to quantify its performance. Any assessment should include close examination of the operation of its mechanical components in ice.

2. FOXTAIL SKIMMER TESTS

BACKGROUND

The performance of the Foxtail VAB 8-14 Oil Skimmer was assessed in North Slope Crude Oil and diesel at the Tesoro Refinery near Kenai, Alaska Dec 2-6, 1991 under the sponsorship of the CPA and the following organizations:

- Cook Inlet Spill Response and Prevention Inc. (CISPRI)
- Alaska Clean Seas
- Environment Canada
- Marine Spill Response Corporation
- Canadian Coast Guard

The skimmer, a 900 kg device, operates through a remote power pack and pump. It incorporates eight vertically-oriented rope mops and is suspended from a crane when deployed. Fabricated by H. Henriksen Mek. Versted AS of Tonsberg, Norway, it is marketed by Nor-Marine of Oslo, Norway and Scan Pacific Enterprises, Inc. of Mukilteo, Washington, USA. See Figure 1.

Primary objectives of the test program were:

- To measure skimmer performance in oil and ice, and record associated machine settings, oil characteristics and ambient conditions.
- To assess operational functionality and suggest modifications which have the potential to improve skimming.

TEST FACILITIES

A test pit 8 x 15 x 1.2 m was excavated at the Tesoro Refinery, lined with a synthetic membrane and filled with Cook Inlet water. In addition to the crane utilized to deploy the skimmer, fish totes, Fast Tanks and pumps were used for oil distribution and collection. A 2 270 L demarcated separator with bottom drain enabled quantification of recovered oil and water phases (see Figure 2).

EVALUATION METHODOLOGY

Three independent test parameters were measured: (1) oil type, (2) slick thickness and (3) ice cover. Waves were not a factor in the test pit.

Oil Type

Tests were conducted with North Slope Crude Oil and diesel. The crude oil was allowed to age during the tests, i.e. the oil used in previous tests was applied to subsequent evaluations. Test oils had the following properties:

	<u>Specific Gravity</u>	<u>Viscosity (cSt)</u>	<u>Pour Point (°F/°C)</u>
Crude	0.89 to 0.97	82 - 1,340	-5/-21 to 27/-3
Diesel	0.81	3	< 60/-51

Slick Thickness

Slick thickness was set at 7-8 mm (0.3") to 10 mm (0.4") for most tests to ensure sufficient oil presentation to the mops. Thickness was estimated by dividing the volume of oil distributed for testing by the area containing it. Slick thickness could be directly measured for diesel using a barrel sampler. In the crude, water-detecting paste and a tube sampler were tried but coating was a problem.

Ice Cover

For tests in broken ice, approximately 4/10ths ice cover was utilized consisting of pieces ranging from 15 cm to 0.6-1 m across and 10-23 cm in thickness.

FIGURE 1 FOXTAIL SKIMMER

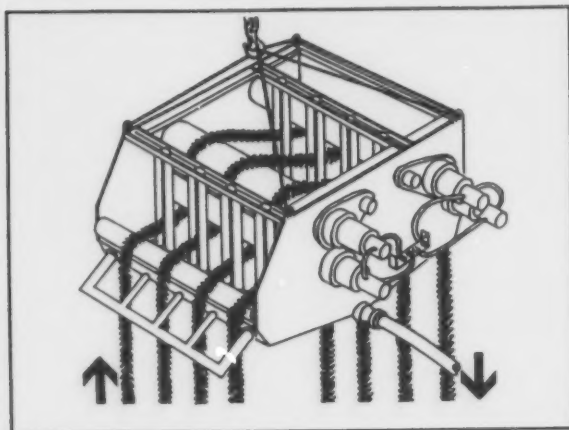
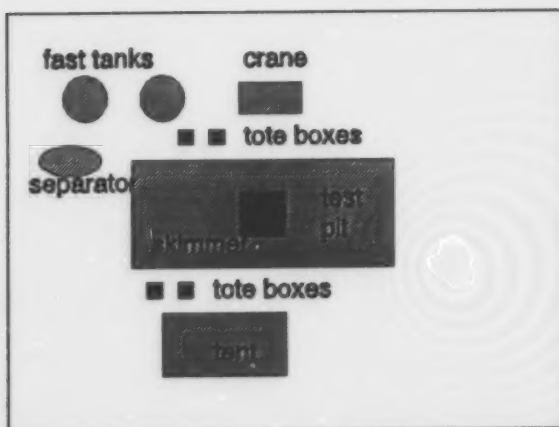


FIGURE 2 TEST LAYOUT



A testing strategy was devised to isolate the effects of individual parameters on skimming in order to optimize machine performance. Skimmer adjustments thus comprised the basis for the tests:

- Mop speed (roller pressure was adjusted once)
- Length of mop contacting water
- Repositioning or sweeping of rope mop during testing

Data recorded for each test run are summarized in Table 1 and included:

- Volume of apparent oil and water phases collected
- Time for liquid recovery (usually 15 minutes)
- Observations re: mop response, mop/wringer performance, safety

Skimmer performance was based on two computed assessment parameters:

Recovery Efficiency (RE) Percent oil in the recovered oil/water mixture.

Oil Recovery Rate (ORR) Net oil collection rate (accounting for water in the recovered liquid).

Samples of the test oil and liquid recovered by the skimmer were collected and tested by laboratory analyses for viscosity, pour point and water content.

Environmental conditions were also recorded during each test:

- Air temperature (generally varied between -1°C (30°F) and 1°C (34°F))
- Water temperature at the oil/water interface [generally 32°F (0°C)]
- Wind speed (estimated at 0 - 10 knots during the tests) and direction
- Weather conditions such as precipitation and cloud cover.

Test data were summarized for each trial run and appear in the final report.

TEST PROCEDURE

Initial shakedown runs allowed personnel to familiarize themselves with operation of the complete system and to "prime" the polypropylene bands with oil. These also facilitated the selection of a range of rope mop speeds, rope mop lengths contacting the water, and collected liquid storage and transfer needs for the tests.

Testing was then conducted over a five-day period, with evaluations first run in open water using crude and then diesel oil, followed by trials with crude in broken ice. For each test, a pre-determined rope mop speed was first established followed by deployment of a known length of the rope mop in the test oil. The addition of high pressure hot water to the incoming mops was also tried.

TABLE 1 TEST DATA SUMMARY

OIL PROPERTIES			ROPE MOP			RECOVERY		
Pour Pt (°F/°C)	Visc (cSt)	Thick (mm)	Speed (ft/s)	Length (ft)	Tot Liq (gal)	App Oil (gal/%)	Oil (gal/%)	Water (gal/%)
TEST SERIES A - Open Water, Crude allowed to age during test								
25/-04	949	.2/5	1	6	400	237/59	--	163/41
27/-03	931	.2/5	1	12	400	251/63	--	149/37
29/-02	1,340	.3/7-8	.75	6	350	75/21	50/14	300/86
25/-04	972	.3/7-8	.6	6	270	20/7	11/04	259/96
TEST SERIES B - Open Water, Fresh Crude								
13/-11	299	.4/10	1	6	400	360/90	181/45	119/55
13/-11	286	.4/10	.75	6	350	207/59	--	143/41
TEST SERIES C - Open Water, Diesel								
-60/-51	3	.2/4	1	6	50	25/50	06/12	44/88
-60/-51	3	.3/7-8	.75	6	100	50/50	38/38	62/62 diesel/crude
-60/-51	-	.3/7-8	.75	18	100	15/15	--	85/85
-60/-51	5	.3/7-8	.75	18	150	40/27	14/09	136/91
TEST SERIES D - 4/10ths Ice Cover, Crude allowed to age during test								
-60/-51	7	.4/10	1	6	150	80/53	45/30	105/70 stationary
01/-17	179	.4/10	1	18	320	200/63	79/25	241/75
10/-12	316	.4/10	.75	18	250	125/50	64/43	186/57
12/-11	421	.4/10	.75	6	200	50/35	22/11	177/89
15/-09	1,111	.4/10	1	18	450	170/38	57/13	393/87
17/-08	851	.4/10	1	18	520	120/23	54/10	466/90 hot water
TEST SERIES E - 4/10ths Ice Cover, Aged crude from previous tests								
20/-07	944	.4/10	.75	18	270	100/37	41/15	229/85
20/-07	950	.4/10	.75	18	550	110/20	69/13	481/87 hot water
25/-04	1,469	.4/10	1	6	420	200/48	84/20	336/80

DISCUSSION OF RESULTS

The Foxtail Skimmer operated optimally in thicker oil slicks of mid-viscosity (100 - 700 cSt) oil within a relatively narrow range of mop speeds: 0.2 to 0.3 m/s (0.75 to 1'/s). At higher speeds, water pickup is evident as well as excessive spray and lower efficiency of operation. Figure 3 indicates the higher total liquid recovered for crude oil versus diesel and the incremental increase in recovery rate with increased mop speed. Figure 4 shows that Recovery Efficiency (oil content) peaked with 5.5 m (18') of mop in the water travelling at 0.2 m/s (0.75 '/s).

The rope mops pick up large volumes of water if they are deployed in relatively thin slicks and contact the underlying water phase. This points to the importance of containing and concentrating slicks for most efficient use of the Foxtail Skimmer. Higher Recovery Efficiency is expected when the skimmer is deployed in slicks of several inches (>4-5 cm).

The length of rope mop in the water appears to have less effect on Oil Recovery Rate and Efficiency than does oil viscosity. The skimmer can be operated with 1.8 m (6') or 5.5 m (18') of rope mop in the water and performance is comparable for any given oil viscosity. In ice, 1.8 m of rope mop could be readily made to "walk" across the oil and ice so that the rate of forward advance matched the rope mop speed. The rope mop did not tangle in ice when 5.5 m was deployed; however, entanglement is possible in large floes with higher edges.

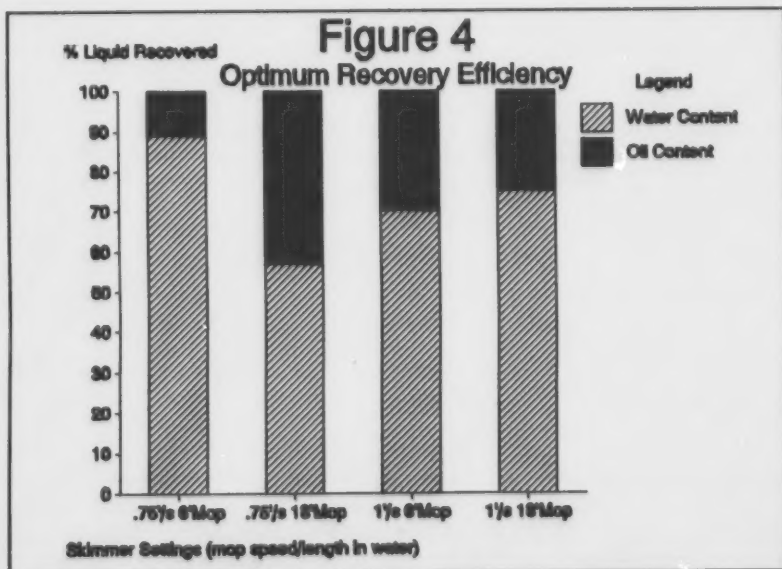
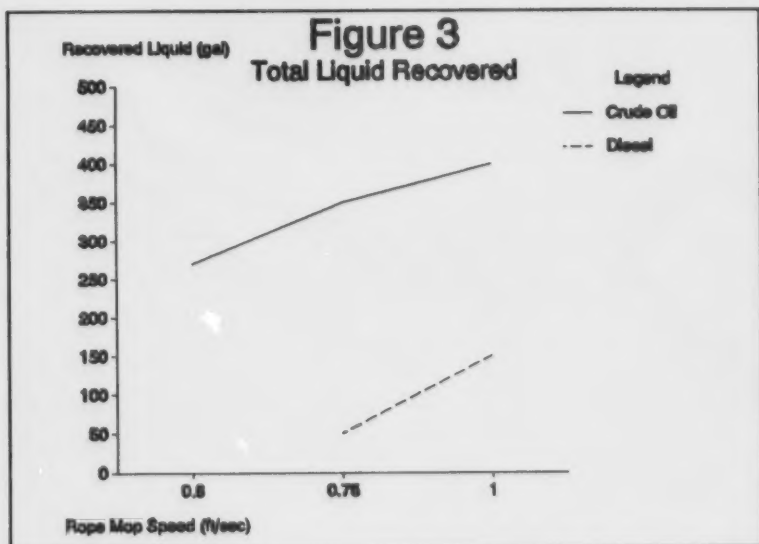
Although testing involved timed trials of 15 minutes each so that a common base was established, it was observed that for the mid-range of crude viscosities tested, most oil pickup occurred in the first 5 or so minutes of operation. Thereafter, recovery rate in the remaining thin slick was lower and water uptake significant.

The skimmer was observed to recover oil more effectively when advanced in the same direction as the mop travel, i.e. toward the downward moving side. When moved in the opposite direction, ice pieces were pushed away from the skimmer along with oil. There is obvious merit in sweeping the mops rather than keeping them stationary as slicks are removed.

In the thinner slicks, the inside six mops play a minor role in pickup as compared with the outer two mops. (Use of the two and four band Foxtail Skimmers were discussed as possibly being more efficiently used in sweeping slicks.)

At viscosities exceeding 1,000 cSt or so, the rope mops tended to mat and recovery rate was reduced. The Foxtail did not recover diesel (0 - 5 cSt) at significant rates (see Figure 3).

Hot water at high pressure [66°C (150°F) @ 5170 kPa (750 psi)] introduced via a nozzle over each mop prior to the wringer did not result in increased Oil Recovery Rate but did add substantially (over 380 L or 100 gal per 15 min) to the water recovered.



CONCLUSIONS & RECOMMENDATIONS

1. The Foxtail Skimmer comprises an oil recovery concept that has excellent potential and affords versatility for many oil-in-ice applications.
2. The diesel/hydraulic power pack operated without mechanical problems during the entire test period and appears to be a reliable package.
3. Skimmer performance is optimal at rope mop speeds of 0.2 -0.3 m/s (0.75 to 1'/sec) and in medium range viscosity oils. Mop height above the water appears to have less influence on Oil Recovery Rate. The unit is significantly less effective in diesel using the type of rope mop tested.
4. The Foxtail should be utilized in contained, concentrated slicks at least several inches thick (>4-5 cm) to operate effectively. Otherwise, the rope mops will pick up significant volumes of water upon contacting water below thin slicks. A flatter mop cross-section would improve Recovery Efficiency in such situations. Use of a 2 or 4 band Foxtail might also be considered.
5. The addition of hot water or steam nozzles is of questionable value. It did not augment skimmer performance.
6. Relocation of the pump to the sump in the puller/wringer should be considered to enable oil transfer from any vessel serving as the working platform.
7. Additional modifications should be reviewed including reconfiguration of the guide rollers and larger entry roller so that the wringing of liquid prior to entry into the wringer is reduced. A readout for mop speed and scale for the speed control lever should also be considered.
8. Pump and hydraulic connections should be specified so that these are compatible with all ancillary hardware associated with the skimmer's intended usage by North American purchasers. Metals compatibility also requires review.
9. Deployment of a Foxtail from a vessel of opportunity requires preplanning of the crane required for suspending the skimming head, the length of discharge hose, the placement of guide ropes, and liquid storage needs. Safe use of the unit in wave conditions also requires assessment.
10. Sea trials in broken ice should examine the ease of positioning the vessel and manoeuvring the mop in various ice forms so that entanglement does not occur. Associated logistical requirements should be assessed (mainly liquid storage) as well as the condition of the mops in below-freezing temperatures. Utilization of a smaller 4-band unit should be considered for such tests in order to assess its capability in ice.

DEVELOPMENT OF A WATERJET BARRIER FOR OIL SPILL CONTAINMENT

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ABSTRACT

A high pressure waterjet barrier is a concept that has shown promise as a means for oil spill containment in cases where a high water current is present, such as in rivers or tidal estuaries. A number of projects have been conducted over the past decade to develop a system of this type for field use. As the barrier's performance has been limited significantly by its flotation system during past deployments, recent work has been directed toward an improved low drag flotation system. This work included a review of the past performance of the barrier and a redesign of the barrier's general arrangement and flotation system. Towing tank tests were performed using full scale models of two alternative float designs. The current-induced drag of these floats was significantly reduced, to 30% and 60% of the original disc floats. A prototype system with boom arms 12m (40 ft.) long was constructed and a preliminary deployment took place in the St. Lawrence River at Prescott, Ontario during August 1991. A comprehensive series of deployments has been planned for the summer of 1992 at the same location.

BACKGROUND AND OBJECTIVES

Currently available oil containment booms are unable to function effectively at sites where the water current exceeds about 0.5 m/s (1 knot) and/or the wave conditions exceed about Sea State 3. There is a need to contain oil spilled in higher currents and sea states such as may occur in rivers and harbours. In recognition of this need a series of projects have been sponsored by Environment Canada and the U.S. Minerals Management Service (MMS) to develop a high pressure waterjet barrier for oil spill containment. Laboratory tank tests (Meikle, 1983; Meikle et al., 1985; Hebron, 1985; Phillips et al., 1987; and Laperriere et al., 1987) and trial field deployments (Laperriere, 1985; Punt, 1990) have been conducted. These tests have shown that the waterjet barrier has promise as a means for oil spill containment in high current or more severe wave situations.

However during past deployments the performance of the waterjet barrier has been limited by the effectiveness of its flotation system. As a result, Fleet Technology Limited (FTL) was contracted by Environment Canada and the U.S. Minerals Management Service to redesign the flotation system and to produce a prototype for testing (Comfort and Paterson, 1991). The objective of this work was to produce a flotation system that would improve the manoeuvrability, directional control, and the stability of the waterjet barrier in the presence of high velocity water current.

REVIEW OF EXISTING SYSTEM AND PROBLEMS DURING PAST DEPLOYMENTS

Conceptually, the waterjet barrier consists of a large capacity, high-pressure pump connected to a series of nozzles that are elevated above the water surface and which are arranged to produce a horizontal spray pattern that opposes the spread of the oil on the water surface.

The "original" (i.e. pre-1991) system used flexible hydraulic hoses to feed water to the nozzles; disc-shaped floats supported the nozzles and the hoses. There was no rigid structure joining individual floats or nozzles. The waterjet barrier has been deployed in two general configurations:

- a) in two arms as a "Vee", which confines the oil at the apex of the "Vee" (see Figure 1 and Plate 1); and:

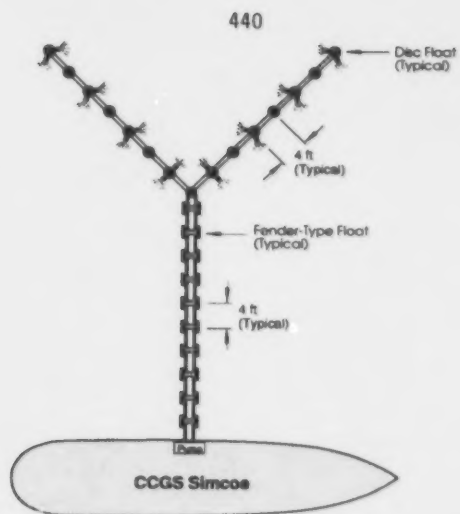


**Figure 1: Waterjet Barrier Configuration Tested at Prescott, Ontario
(By Punt, 1990)**



Plate 1: Waterjet Barrier During 1990 Trials at Prescott, Ontario

- b) in a single arm, which is intended for applications where the oil is to be diverted (such as to a cleanup site on shore for an oil spill on a river).

For each operating configuration, the nozzles are located on 2.4 m (8 ft.) centres and are arranged such that opposing horizontal jets are produced. This general arrangement allows the arms of the barrier (for the "Vee" configuration) or the whole barrier (for the "diversionary" mode) to be manoeuvred using differential water pressure, controlled from a central manifold off of the high pressure pump. It also acts to stabilize the system while operating.

The most recent deployment of this "original" system was conducted in 1990 at Prescott, Ontario (Punt, 1990). A number of problems were experienced at that time. The disc floats had excessive drag such that in a current of 0.5 to 0.75 m/s (1 - 1.5 knots) the barrier could not be manoeuvred and kept on station in the desired configuration (ie. with the desired angle between the arms of the barrier). The arms were also found to be too flexible, with the result that the system was difficult to control. Stability problems occurred as the disc floats overturned in some cases (see Plate 1). Also the height of the nozzles above the water in the original system was less than that identified for optimal oil retention performance (by Phillips et al, 1987) in laboratory tests.

REVISED DESIGN: CONCEPT DESCRIPTION

Several approaches were considered for improving the waterjet barrier design. The alternatives fell into two general categories, as follows:

- a) flotation system improvements, and;
- b) general arrangement improvements.

A combination of both was utilized, as illustrated in Figure 2.

The flotation system revisions consisted of:

- 1.) use of an "airfoil-type" float that was able to "weathervane" in the current.
- 2.) a reduction of the number of floats by spacing them at 2.4 m (8 ft.) centres, rather than at 1.2 m (4 ft.) centres as in the "original" design.

The general arrangement of the system was also changed. To reduce the flexibility of the waterjet barrier and reduce the number of floats required, it was decided to support the hydraulic hoses rigidly with aluminum square tube sections between the floats. Each support is pinned together to allow movements in the vertical direction.

Past experience had shown that it is desirable to allow the angle of the arms at the apex to vary for improved oil retention performance. To achieve this, the arms of the barrier were pinned vertically at the apex structure.

It was recognized that the revised design was more complex than the "original" barrier. These revisions were considered necessary in order to resolve the problems experienced with the original system during previous deployments.

DESIGN OF THE WATERJET BARRIER FLOATS

Objectives of the Float Design

The new floats were designed to meet three main performance objectives:

- 1.) Support the weight of the barrier and maintain a nozzle elevation of approximately 20cm (8") above the waterline.
- 2.) Improve the stability of the barrier under the action of the water jets.
- 3.) Reduce the drag of the floats in current up to about 2 knots (1 m/s).

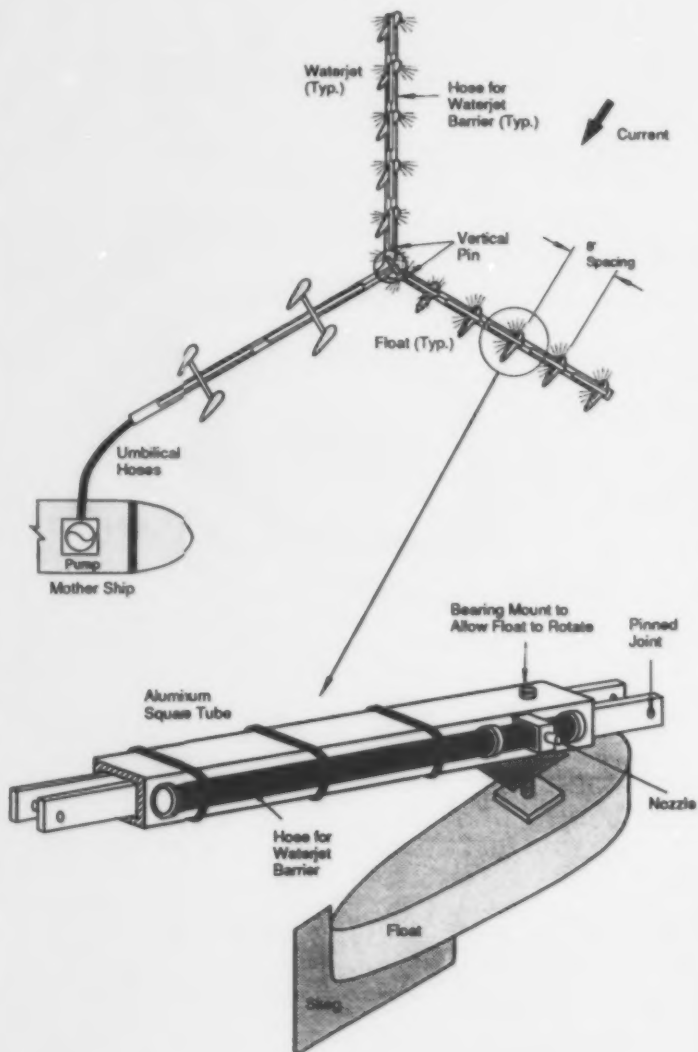


Figure 2: General Arrangement of Revised Waterjet Barrier

The actual float configuration was driven by objective "3", reduction of the float drag, although achievement of the first two objectives were necessary for any successful float design. The review of past designs indicated strongly that drag reduction was critical for providing acceptable station-keeping performance and controllability of the waterjet barrier.

Selection of the Float Hull Form

A number of float concepts were generated, including the possibility of retaining a circular float form. The design effort quickly focused on the "airfoil" type float as the form offering the greatest potential drag reduction, and favourable motion characteristics in waves. However the selection of an airfoil form introduced the requirement that the float must "weathervane" to maintain a favourable (ie. low drag) heading into the current. Two variations of the airfoil float were evaluated for use on the boom arms, as shown in Figure 3.

Concept LF1: the Short Airfoil or the "Airfoil Strut" float.

The basic sectional shape was conceived as a section with an elliptical nose and parabolic tail, offering the best potential weathervaning response. A "standard" airfoil section, with a length of 1m, an L/B ratio of 4, and the maximum breadth at 30% of the length, forward was designed from Hoerner (1965). The concept was developed as a strut ie. greater depth to length, in order that heave (vertical translation) would be the dominant motion response in waves.

The major penalty associated with the "strut" concept was its short length, which would result in a higher speed:length ratio at the upper speed range. It was unclear whether the superior form drag of the float would offset the resistance penalty associated with the wave system developed at a high speed:length ratio. An additional penalty was that the float would be highly laterally unstable due to the low centre of buoyancy. This was a concern during boom deployment and because of the potentially large moment that would be placed on the float pivot bearings.

Concept LF2: the Long Airfoil or the "Boat Hull" float

This variant was longer with a much shallower draft than the SF1 concept. Producibility and durability concerns precluded more complex hull shapes and finer hull sections, while the weathervaning requirement introduced a length limit. Standard ship hull form ratios provided guidance with regard to L/B ratio and the relative influence of other hull parameters. To obtain similar motion responses to the short airfoil concept, the beam was restricted to the same range (0.2 -0.3m). This resulted in a slender, deep, hull form. A standard "slender" form based on an L/B ratio of 6.5, with the nose and tail section of airfoil SF1 and the length constrained to 1.625m to avoid interference between adjacent floats during rotation.

The main attribute of this concept was its increased length, which meant a lower wave making drag. In addition, the concept features a large waterplane area, which allows for weight changes in the structure above, while still featuring a relatively slender hull form, necessary for "platforming" (cutting) through waves. There was a concern that the length constraint produced a float where the extremities are quite "full", ie. have "U" sections and large waterplane area at each end, and therefore may be prone to "pitch" in waves, despite a relatively high L/B ratio.

The main concern with the long airfoil concept was its ability to weathervane; the additional length placed the nose section well forward of the pivot while the parallel midbody resulted in a greater fore-aft symmetry; it was expected that a skeg (fin) would have to be fitted aft.

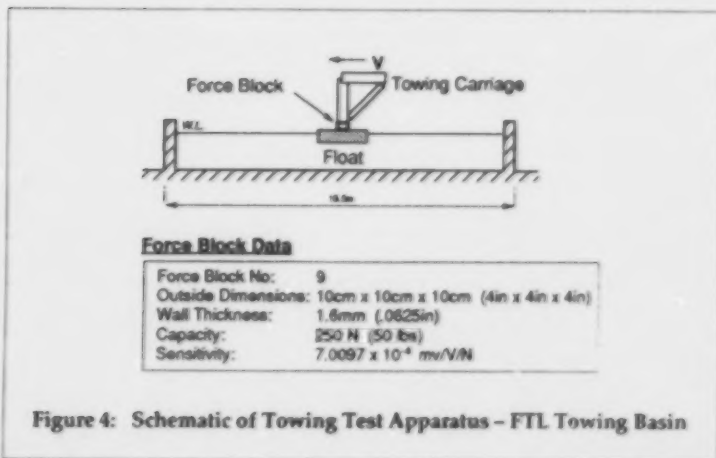
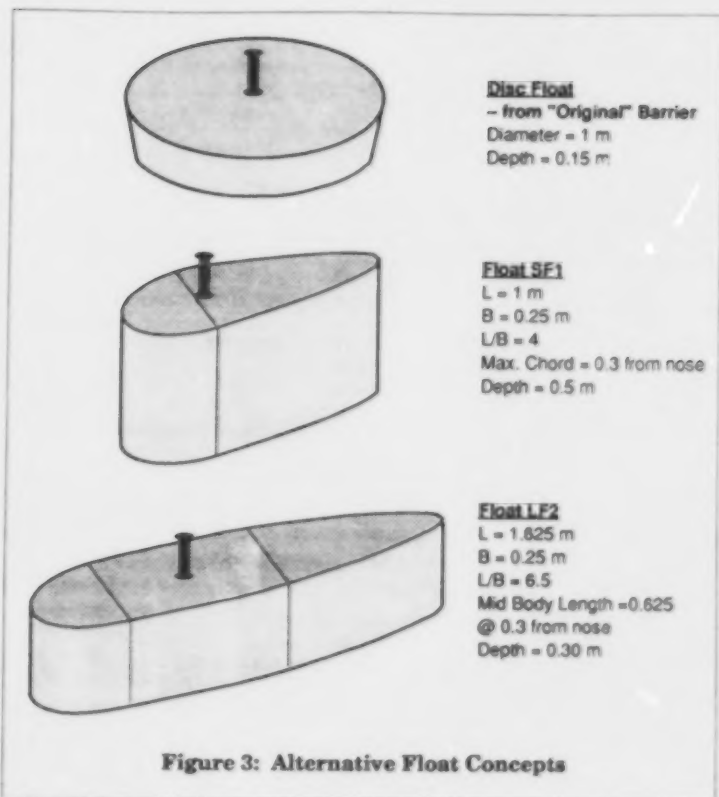


TABLE 1:
Summary of Experimental Resistance Results for Waterjet Floats

Model:		Disk	SF1		LF2	
V(knots)	V (m/s)	Mean Rm(N)	Mean Rm(N)	Calc. Rc (N)	Mean Rm(N)	Calc. Rc (N)
0.58	0.3	2.24	0.69	0.86	0.65	0.87
0.58	0.3	2.34	-	-	0.53	-
0.97	0.5	6.38	2.09	2.11	1.08	1.66
0.97	0.5	6.38	1.92	-	1.04	-
1.36	0.7	12.25	4.55	4.32	2.00	3.40
1.36	0.7	12.35	4.64	-	2.38	-
1.55	0.8	-	6.80	-	3.73	-
1.55	0.8	-	7.14	-	3.35	-
1.75	0.9	-	11.41	-	5.84	-
1.75	0.9	-	11.31	-	7.58	-
1.94	1	25.25	15.12	7.20	9.16	5.70
1.94	1	25.45	15.14	-	8.16	-

Note: Velocities are nominal based on Speed Control Setting

1.1 Measured Thrust Developed By Waterjet:

- 1) At 500 psi: Thrust = 62.4 N
- 2) At 1000 psi: Thrust = 106.4 N

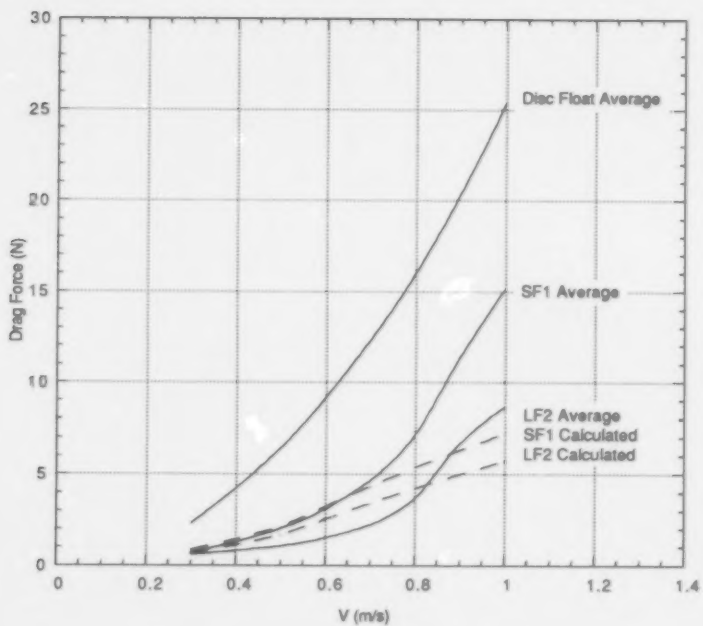


Figure 5: Measured Drag Versus Towing Speed



a) SF1



b) LF2

Plate 2: Comparison of Wave Systems at High Speed; SF1 and LF2

Evaluation of the Airfoil Float Concepts

The evaluation of the two float configurations was based on tests conducted in FTL's towing basin in Kanata using full scale prototypes. These trials had two phases:

- 1.) Resistance trials to measure the total drag on each of the prototypes; it was found that the long airfoil (LF2) had the lowest drag.
- 2.) Determine the weathervaning characteristics of the float with least resistance (LF2); development of an appropriate skeg.

Results of Resistance Trials

Resistance tests were performed on three different models:

- 1.) the disk float - used in the "original" flotation system, as a baseline for evaluation
- 2.) the airfoil float SF1
- 3.) the boat hull float LF2

Refer to Figure 3 for sketches and the dimensions of each float.

The trials were performed over a nominal speed range of 0.3 - 1.0 m/s (0.6 - 2 knots), with approximate increment of 0.25 m/s. At least two tests were performed at each speed, and additional tests were performed at smaller speed increments at the higher speeds where resistance (drag) increased dramatically. A schematic of the towing arrangements is shown in Figure 4. The mean measured resistances for each model are given in Table 1 and plotted in Figure 5.

Numerical drag estimates were prepared for each of the candidate float and the original disk float, based on the empirical formulae found in Hoerner (1965) and Comstock [PNA] (1967). It should be noted that the numerical analysis did not contain an estimate for the wave-making drag component, as no simple formula was available for these forms. Consequently the accuracy of the drag estimates was expected to change dramatically as speed increased and the wave-making component became more significant. The numerical drag estimates are included in Table 1 and plotted in Figure 5.

The data clearly shows that float LF2 had the lowest drag of the floats tested. The model tests indicated that this float has approximately 30% of the drag of the baseline disk float at the design speed of 2 knots (1 m/s). The short airfoil float had a higher drag, largely due to the wave making resistance. This conclusion was supported by observations of the wave pattern associated with each float shown in Plates 2a and 2b, which show a significant wave system associated with the short airfoil float (LF2) at the design speed. Thus it was determined that the additional length of the long airfoil, which reduces the speed:length ratio (or Froude Number) and thereby the associated wave-making action, was the key factor in minimizing the float drag.

A separate set of tests were conducted to measure the reaction force exerted from a single waterjet nozzle. The object was to compare the force created by the nozzle with the hydrodynamic drag forces on the float. The results of these tests are also included in Table 1. The results suggested that there will be adequate nozzle thrust available to manoeuvre the barrier on correctly weathervaning floats.

Weathervaning Trials

The second part of the model trials involved testing the weathervaning capability of the LF2 float design, selected for development following the resistance trials. The model was fastened to the towing post through a roller bearing that allowed the model to freely rotate in yaw (i.e., in the plane of the water surface). The model was towed from an initial angle to the direction of towing. The turning response of the model as it was being towed

was recorded on videotape. No force data was collected. The response of the model was judged on whether it aligned itself fully with the towing direction over the length of the trial.

The weathervaning trials were performed systematically over a range of initial orientations, consisting of 0, 45, 135, and 90 degrees to the towing direction. The model was towed at 0.5 m/s for most runs, followed by low speed tests at 0.3 m/s and a high speed test at 0.7 m/s.

The initial trial was performed without any skeg. These tests indicated that a skeg would be necessary to achieve the required weathervaning performance. A skeg is simply a flat vertical plate fitted to the stern of the float which would alter the pressure distribution along the float length without adding displacement.

After some experimentation, a skeg configuration using an "L" profile, with the foot of the "L", or keel, running forward under the float to the parallel midbody was selected. This configuration was selected because it offered the best increase in skeg area for the minimum increase in length and depth of the float. Restricting the depth of the float was desirable for deployment in shallow water, and for durability. The skeg arrangement is shown in Figure 6 which shows the general arrangement of the float.

Initial Design of the Umbilical Floats

Along the umbilical structure connecting the waterjet boom arms to the pump there are four hoses (instead of two) so the supporting floats have to be correspondingly larger. There was additional displacement required for the float at the junction of the "Y", because of the weight of structure located at the apex. It was proposed to obtain the added buoyancy using the LF2 float waterplane section with additional depth, rather than an overall increase in dimensions. See Figure 6. The result was a deeper float which was much less stable than the boom arm floats but was very simple (and less costly) to construct, because a common mould could be used, as described below.

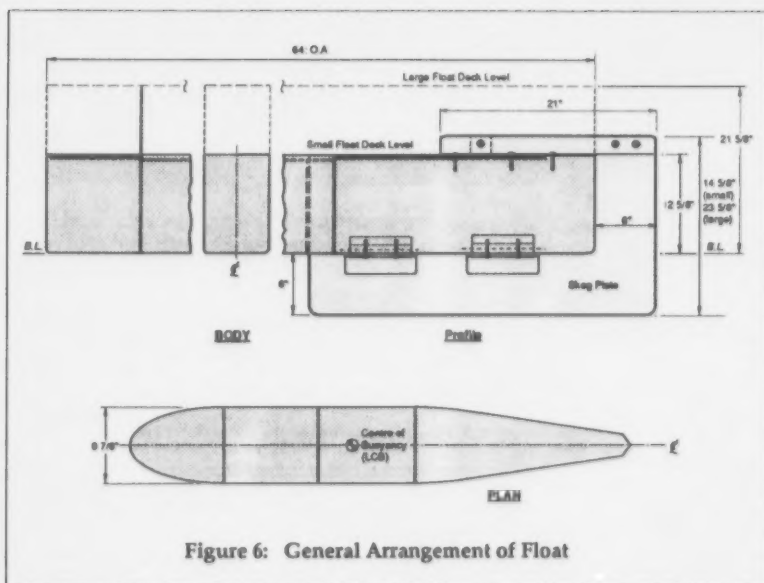
It was subsequently found in the initial deployments that the umbilical floats had an unacceptably high profile and poor stability, which could limit the mobility of the barrier. A revised umbilical flotation system was designed that is described below.

Fabrication of the Waterjet Barrier Floats

It was decided to employ conventional fiberglass boat building methods to efficiently produce the quantity of floats required for the complete waterjet barrier. This technique is suited to quantity production because a re-useable mould is used to produce the hull shell. In addition, this mould was designed with sufficient depth to manufacture both sizes of float, for the boom arms and the umbilical structure.

The hull shell is made of fiberglass formed over the mould, with a hard smooth, Gelcoat exterior. The shell is reinforced with 3/4" (1.9cm) plywood transverse frames and a full-length 3/4" plywood deck. The float skegs were fabricated in 3/16" (0.5cm) aluminum, and attached to the float hull through 2"x 2"x 1/4" (5cm x 5cm x 0.635cm) aluminum angle brackets. The edges of the keel plate angle were extensively rounded (faired) to minimize parasitic drag. The entire skeg assembly is designed to be removable in the event of damage to the skeg plate.

The floats are connected to the boom structure through a pivot post consisting of 1" (2.5cm) rod welded to a flat metal baseplate, which is secured to the float deck by four heavy screws.



REVISIONS TO THE BOOM OUTFIT

It was expected that some constraint on the weathervaning action of the floats might be required, particularly during deployment and during low current conditions. Subsequent preliminary deployment trials, discussed below, verified this. Because the floats are slender, with weight of the boom arms well above their centres of buoyancy, the individual arm can capsize should the floats align too closely with the axis of the boom arm. Two types of float constraint are fitted, which allow the float to weathervane through an angle of about 90°:

- 1.) Stops fitted to each float, as shown in Figure 7a.
- 2.) Linking cables joining each float at the skeg, such that they weathervane in unison as shown in Figure 7b. A level of redundancy is also introduced should a stop fail.

A review of the deployment problems with the earlier boom designs suggested that the reliance on the waterjets to maintain position and control was excessive. It was recognized that deployment would be simplified by physically constraining the movement of the arms and of the boom position; the waterjet action would then be used for "local" control of the boom position and orientation. Thus two types of constraint are proposed, as shown in Figure 8:

- a) Cables linking the individual boom arms; when fully extended the boom will be maintained at a specific limiting angle. The waterjet action will allow the operator to vary the boom opening angle from the limiting angle.
- b) An anchor (or anchors) to maintain the basic position of the boom. The waterjets will allow the operator to move the boom around the anchor position.

PRELIMINARY DEPLOYMENT EXPERIENCE

A preliminary deployment of the revised waterjet barrier took place in late August of 1991 at the Coast Guard Base at Prescott, Ontario. Somewhat ironically, the weather during the trial period was generally characterised by high winds (+30 knots) and waves up to 1m. Because this was the first deployment of the revised boom, only a single deployment was attempted under these conditions, in the shelter of a small boat basin at the base. A photograph of the deployed boom is shown in Plate 3; note the boom was tethered from the ends of the boom arms.

The following conclusions were drawn from this deployment:

- 1.) It was demonstrated that the boom could be controlled under calm conditions by varying the waterjet pressures. The boom opening angle and the orientation of the boom could be varied using differential waterjet pressure controlled from the pump manifold.
- 2.) The revised flotation system was found to float at the design waterline such that the waterjet nozzles were placed at the appropriate elevation above the water surface. See Plate 3.
- 3.) Prior to activation of the waterjets, the boom was found to be affected by the high winds despite a relatively low profile above the water. In the absence of water current, the wind would tend align the floats with the barrier structure, such that the structure could capsize. The single umbilical floats, which had a higher above-water profile were most affected. This observation resulted in a couple of actions:
 - a) The single umbilical floats were replaced by a catamaran system of smaller floats, as shown in Figure 2. This revised arrangement should be more stable and will have a lower profile, but has not yet been tested.

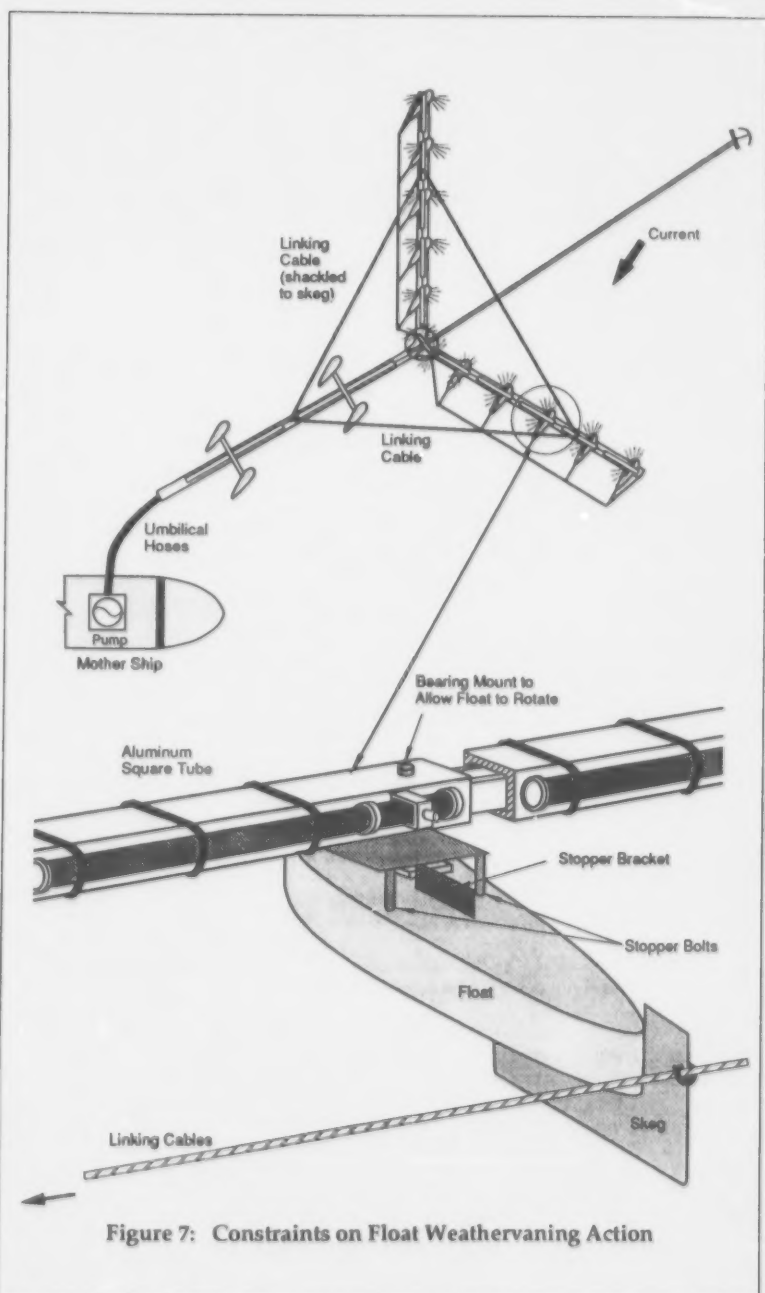


Figure 7: Constraints on Float Weathervaning Action

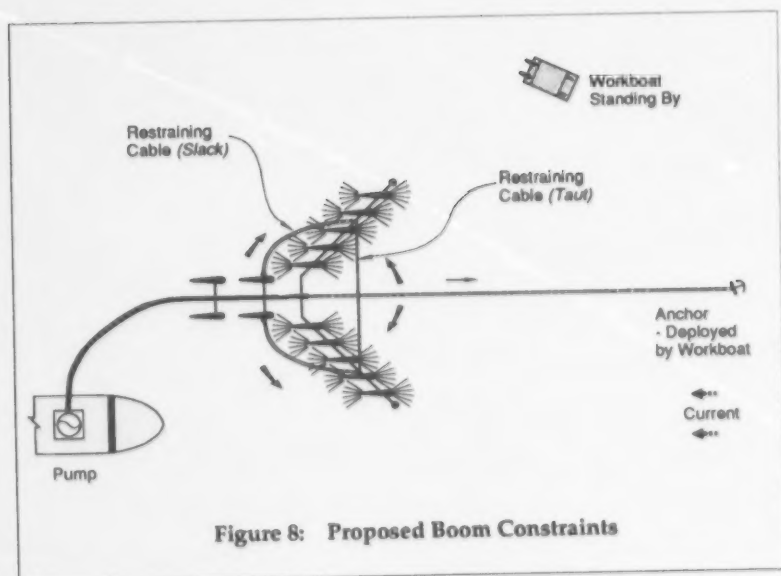




**Plate 3: Deployment of Revised Boom in Small Craft Basin
CCG, Prescott, August 1991**

- b) The weathervaning constraints consisting of the stops and the skeg linkages were found to be necessary to counter the wind, and in fact had to be reinforced during the deployment.
- 4.) The individual boom arms were exposed to waves estimated to be 0.3- 0.6m during the trials, and the wash from passing ships. The arms were observed to ride the waves and maintain a horizontal attitude.
- 5.) Revisions to the hose connection system would facilitate deployment. The current system uses pairs of threaded connections which require considerable effort to connect. However the current system will be retained for the proposed series of trials which are intended to demonstrate the waterjet barrier concept.

PLANNED FURTHER DEPLOYMENTS

Encouraged by the experience obtained during the preliminary deployment, a more comprehensive set of trials is planned for the summer of 1992. These trials will encompass a series of phased deployments under field conditions at CCG Prescott. The trials are intended to evaluate the controllability of the boom under the prevailing current and wave conditions from a shore location and in mid-river from a base vessel. The containment effectiveness will be assessed using canola oil to simulate an oil spill. Water pressures will be monitored from gauges fitted at the pump manifold. The results of these trials will be used to evaluate the overall effectiveness of the waterjet barrier concept and recommend improvements to the current waterjet barrier configuration.

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THE CONTAINMENT OF HEAVY OIL IN FLOWING WATER

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ABSTRACT

Viscous Bitumen from the oil sand deposits of Northeastern Alberta is diluted with a gas condensate before transport by pipeline to distant markets. Because of its unique properties, the diluent / bitumen mix (Dilbit), may require novel containment and recovery techniques should an accidental spill occur. Preliminary experiments have been conducted in a large flowing water channel to determine if several conventional containment devices could be utilized to trap weathered and emulsified Dilbit and Bitumen. These studies indicate that conventional barriers need improvement to be effective at higher water velocities and suggest that new concepts in containment should be considered.

INTRODUCTION

A substantial percentage of Canada's crude oil production comes from the large reservoirs of bitumen in Northeastern Alberta. Some of this heavy viscous material is upgraded to a synthetic medium gravity crude suitable for refining, but much of the production is marketed in essentially the form it is produced. The bitumen as produced cannot be transported by pipeline unless its viscosity is lowered by diluting it with some miscible less viscous liquid. Large quantities of bitumen are transported by pipeline from Imperial Oil's Cold Lake production facility by adding a gas condensate to the bitumen. Some of this mixture, known as Dilbit, is transported over significant distances. The various markets for Dilbit include the U.S. Midwest, Ontario, and the Far East, which is supplied through the Port of Vancouver.

In the unlikely event that a spill occurred during the pipelining, ship loading or transport through Canadian coastal waters, spill responders would need to know the most appropriate techniques for recovering it. This study is a preliminary examination of three well known boom types to determine the relative water velocities at which failure occurs for each of three bitumen and diluent blends. The behaviour of the oil samples during boom failure was noted.

MATERIALS AND EXPERIMENTAL DESIGN

Experiments were conducted in a flowing water channel constructed within the Esso Wave Basin in Calgary. The channel has been described previously (Nicholson et al.(1991)). Essentially, it consists of a channel 1m deep by 5m wide by 27m long with an hydraulically powered paddle wheel at one end to drive the water. Water flows of up to approximately 0.5m per second with reasonable cross channel and depth velocity profiles can be achieved. An underwater viewing port suitable for mounting cameras has been constructed into one of the channel walls. A large travelling bridge spans the entire wave basin and can be used for mounting equipment over the channel at any location. Because of the size of the channel, portions of containment booms could be tested without experimental scaling.

Oil samples of three different viscosities and densities, which represented the spilled material likely to be encountered at different times during a spill scenario, were used during the experiments. The oils and their properties were as follows:

- a) **Dilbit Weathered 24 Hours** - This oil represents the spilled material which responders would likely encounter after about 24 hours, where the spill had occurred on calm water. Much of the gas condensate component would have evaporated but the material properties would still not have reached those of undiluted bitumen. The weathered oil was prepared by allowing Dilbit to stand at ambient outdoor temperatures (overnight lows of 15°C and mid-day highs of 25°C) in shaded 1m by 2m trays. The oil depth was 2 cm. The density of this material ranged from 0.978 to 0.982 and had a viscosity of from 12400 cp to 18400 at 15°C depending on the batch.
- b) **Bitumen as Produced** - Dilbit which had weathered for a number of days would ultimately have the properties of bitumen and would present different recovery problems for spill responders. Typically the density of this material is 1.001 at 15°C with a viscosity of about 10⁵cp. In fresh water this material floats in mid-column and in sea water is easily over-washed by small waves.
- c) **Emulsified Weathered Dilbit** - Dilbit readily emulsifies when subjected to either fresh or sea water waves. Dilbit weathered for 24 hours was emulsified with either fresh water or an artificial sea water mix by gently tumbling the Dilbit and water in a ten gallon drum. The drum had three vanes welded to the inside surface at 120° to the axis of rotation and was turned on a drum roller at 28 rpm for 30 minutes. The resulting emulsion was allowed to settle for 5 minutes and then decanted. It remained stable during the experiments but broke after sitting for 2 days. The water content of the emulsion was approximately 50%.

Spilled Dilbit has unique properties which will probably require containment and recovery techniques different from those used for conventional oils. Three containment barriers, each of which uses a different containment mechanism, were tested with each of the three Dilbit derivatives. There was no expectation that any of the barriers would necessarily be successful with any of the fluids employed, but the hope was to understand more completely the mechanisms by which each of the containment devices ultimately failed. The devices used in the experiments were as follows:

- a) **Conventional River Boom** - A portion of a small conventional river boom was used which had 15cm diameter by 3m long cylindrical styrofoam floats attached to a 15cm deep skirt. Tension in the boom was provided by steel cables running through the floats and along the bottom of the skirt. The boom portion tested in the channel consisted of one 3m float section and two 1.5m float sections at either end.
- b) **Nylon Fine Weave Net** - Previous studies have shown that heavy oils can be trapped with fine mesh nets, although the oil slowly extrudes through the net over time (Morris (1986), Brown (1989)). A 5m long by 0.5m deep nylon braided net with an effective hole size of 1mm x 1mm was used in these experiments. A buoyancy of 2.5kg per metre was provided by elliptical styrofoam floats sewn into the top edge of the net.
- c) **Low Pressure Bubble Barrier** - This barrier consisted of a 10cm diameter canvas hose 5m long held on the channel floor with weights. It was supplied with air from a 2.5 hp ring compressor which could provide 73 litres / sec. open flow volume or 55 litres / sec. air flow at a head of 1 m of water. The canvas hose successfully leaked air in a uniform curtain of fine bubbles.

Each of the containment devices was anchored in turn near the underwater viewing port of the flowing channel about 15 m downstream from the channel baffle. Water flow velocity profiles were measured in front of each barrier using a Price rotating vane type flow meter. Experiments were conducted with mid-channel water velocities varying from approximately 0.15 m/sec to 0.50 m/sec. Video of the movement of various oil samples near each barrier was recorded both above and below the water surface. One litre oil samples were placed onto the flowing water at mid-channel just below the flow baffle and allowed to flow down the channel to encounter each barrier. All tests were conducted with fresh water at ambient water temperature of 15°C $\pm$ 1°C. The oil samples were also near 15°C before placement on the water with the exception of the Bitumen samples. These were cooled to approximately 5°C before placement to ensure that the density would be slightly greater than that of the water. Generally, Cold Lake Bitumen density exceeds 1.000 below 15°C.

No scaling of the fluids or barriers was used in these experiments. Griffiths (1981) has discussed fluid flow around sharp edged objects and concludes that barrier experiments can usually be conducted in a regime independent of Reynolds number (one of the usual scaling factors). For this type of experiment, Reynolds number independence occurs for $Re > 4000$. This condition holds in our experiments if the boom draft is > 2 cm and the water velocity is over 0.2 m per second. The boom draft must be limited however, to about 1/6 th of channel depth if bottom effects are to be avoided.

Both the Bubble Barrier and the River Boom were tested as containment devices in which they were positioned perpendicular to the current and as deflection devices for which they were positioned at an angle to the flow. The Net was used only as a containment device.

RESULTS AND OBSERVATIONS

River Boom

The results of tests of the River Boom with both weathered and emulsified Dilbit are summarized in the table below. Several tests with Bitumen demonstrated that the barrier had no effect whatever on neutrally buoyant material which was carried directly under the barrier.

TABLE 1 RIVER BOOM

VELOCITY (m/sec)	MATERIAL	DENSITY	BOOM ANGLE	COMMENTS ON FAILURE
0.25	Emul-Fresh	0.989	90	Oil retained indefinitely
	Emul-Salt	0.999	90	Oil retained indefinitely
	Weathered	0.983	90	Vortex shedding loss after 250 secs.
0.29	Weathered	0.983	90	Oil retained - but end loss
	Weathered	0.983	90	Vortex shedding loss after 150 secs.
	Weathered	0.983	90	No retention
	Emul-Salt	0.999	90	Oil retained - but end loss
	Emul-Salt	0.999	90	Oil retained
	Emul-Fresh	0.989	90	Oil retained - but end loss
0.33	Emul-Salt	0.999	90	No retention
	Emul-Fresh	0.989	90	No retention
0.36	Weathered	0.983	45	Some diversion
	Weathered	0.978	45	All of sample diverted
0.42	Weathered	0.983	45	No diversion
	Weathered	0.978	45	All diverted
0.48	Weathered	0.978	45	Sample partially diverted

The water velocity shown here was that measured 0.2 m below the surface at a position near the boom centre where the oil usually encountered the boom. A difference of less than 15% was measured in the channel flow profiles with and without the boom. Such differences are probably within the error of setting the paddle wheel speed and measuring the current velocities.

All of the samples of emulsified and weathered Dilbit were carried by the current on the water surface. For these samples there were sufficient light components present to produce a small amount of sheening around the main streamer of oil. When the floating oil accumulated along the River Boom, the first failure was observed when vortices appeared at bends in the boom. A vortex may be created at a discontinuity in the front surface of the boom by a small current velocity component perpendicular to the general flow direction. The pooled oil was observed to flow under the boom in a long thin strand over a period of several seconds. This phenomenon was observed with weathered Dilbit when the mid-current velocity was about 0.25 m/sec. The emulsified oil, which is slightly more dense than the weathered oil but is probably also much more viscous, is not lost as readily by vortex shedding. Nevertheless, in a typical stream deployment, this boom will not reliably contain these dense oils at water currents even as low as 0.25 m/sec.

Boom failure criteria have been developed for less viscous oils by Lau and Moir (1979). They show that containment booms fail by loss of oil from the oil water interface (entrainment failure) when the densimetric Froude number F and the boom draft factor T satisfy

$$F = U_o / (g\Delta d)^{0.5} > 0.5 \quad \text{and}$$

$$T = U_o^2 / (2g\Delta) / (1-\Delta) > \text{boom draft}$$

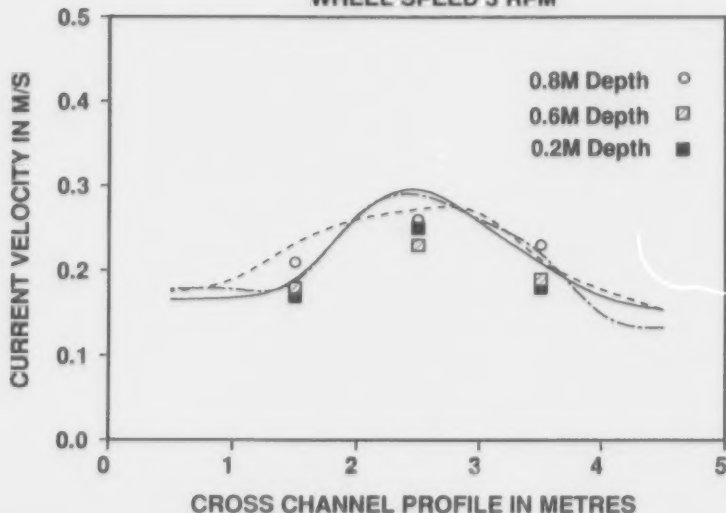
where U_o = water velocity
 d = channel depth
 g = acceleration of gravity
 Δ = ratio of (water - oil) density to water density

For the weathered Dilbit with a density of 0.983, these conditions would be satisfied at a flow of about 0.23 m/sec; that is, failure could be expected at water velocities greater than 0.23 m/sec. Although this is approximately the flow at which failure was observed, the failure mechanism was vortex shedding. Oil loss by entrainment failure was never actually observed. At higher water velocities, the oil was only momentarily stopped by the barrier and was then lost even along straight portions of the boom. Such failures appeared to be due to the critical accumulation loss mechanism described by Delvigne (1989). He has found that oil slicks with viscosities greater than about 3500 cSt collapse suddenly at low critical water velocities and pass in entirety under barriers. Boom failure would be expected with our weathered oil samples with $\nu = 12,500$ cSt and greater at water velocities near 0.20 m/sec. This failure mechanism may have been masked at lower velocities by the observed vortex failure. Given that these tests took place in ideal flows, it may be very difficult to successfully deploy this boom to trap viscous oils under field conditions. A few tests show it may be employed with some success for diverting these oils.

Fine Weave Nylon Net

Water velocity profiles and extrusion rates for the Dilbit oils were measured on a fine weave nylon net which spanned the channel down to half its depth. The net slowed the channel flow rates slightly for a given paddle wheel speed as shown in Figure 1.

FIGURE 1 EFFECT OF NET BOOM ON CURRENT
WHEEL SPEED 3 RPM



A number of simple trapping experiments were carried out with each of the oils to see if the net significantly changed the flow of oil as it reached the net. All of the floating samples of weathered and emulsified Dilbit were trapped by the net and adhered to it. The neutrally buoyant Bitumen samples did not appear to change depth as they were swept near the net and were trapped if they were in the upper half of the water column but otherwise were swept under it.

Extrusion rates were measured by spreading an oil sample as uniformly as possible over a 35 cm by 35 cm area on the front of the net near its centre. This was done with the net resting on a floating board. The net was then quickly released into the water as the water flow was started. The back of the net was observed by means of a remote underwater video camera and the approximate time was noted when extrusion of the sample was complete. The results of these measurements are shown in Figure 2. The solid line indicates the best fit to the data and the outer dotted lines the computed leak rates for nets of similar hole sizes using the equations of Delvigne (1987). These measurements are consistent with the laboratory measurements of Delvigne and earlier mesoscale net towing experiments of Brown (1989).

FIGURE 2 OBSERVED VS: COMPUTED NET
LEAK RATE

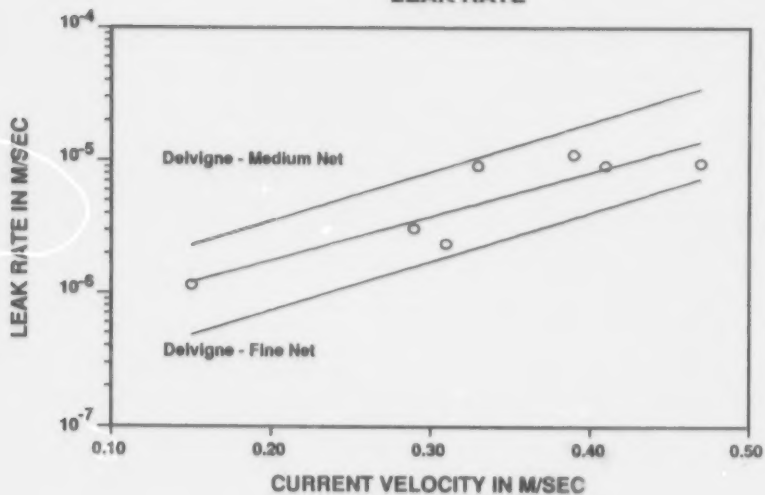
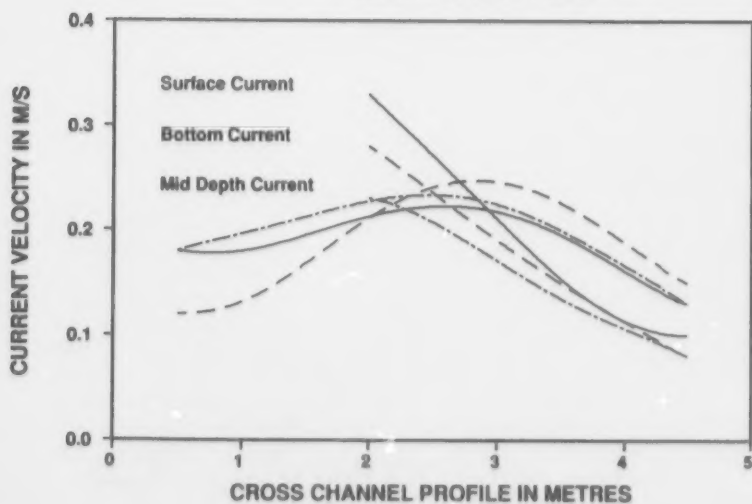


FIGURE 3 BUBBLE BARRIER AS DEFLECTOR
WHEEL SPEED 3 RPM



Low Pressure Bubble Barrier

Bubble barriers have been studied previously as containment devices and some have been permanently installed around tanker loading facilities (Jasinski and Piorewicz (1988)). In concept, bubble barriers contain surface oil by creating a surface current which opposes the gravity spreading of the oil. It is possible that the upward current generated by the bubble curtain might also contain or at least divert heavy oil which floats within the water column.

The bubble barrier was first deployed directly across the channel. With no water current flowing, the bubble stream generated a surface current with a maximum velocity of about 0.5 m/sec in each direction away from the barrier. The maximum surface current is related to the air flow rate into the barrier by (Lau and Engel (1980), Jasinski and Piorewicz (1988))

$$V_{\max} = 1.5 \times (gQ)^{1/3}$$

where Q is the flow rate per unit length of barrier. For $V_{\max} = 0.5$ m/sec, this yields $Q = 3$ litres/m/sec. This is approximately what the pump is capable of delivering at a depth of 1 m water pressure together with the back pressure of the canvas hose.

Surface floating samples of weathered and emulsified oil were stopped by the barrier only for short periods even at low water currents of 0.23 m/sec. Usually the barrier slowly leaked the surface oil at variable points along the bubble curtain where nonuniformities in the bubble train appeared. The barrier was even less successful with samples of neutrally buoyant oil. Litre sized globules of oil floating in mid column would occasionally be diverted upward for a few seconds but would then swoop back down and pass unhindered through it. Not only would the main globule of oil pass through the barrier but small droplets and strings of oil would be torn from it and dispersed in all directions. The bubble barrier was ineffective for this dense oil at velocities above 0.15 m/sec.

TABLE 2 BUBBLE BARRIER

TEST	MID-CHANNEL VELOCITY (m/sec)	SAMPLE POSITION IN WATER COLUMN	BARRIER BEHAVIOUR
1	0.33	bottom sample	No diversion of sample
2	0.28	mid-column	Barrier 60° to flow; oil not diverted
3	0.28	bottom sample	Barrier 30° in following tests/oil not diverted
4	0.28	mid-column	Oil diverted twice
5	0.28	bottom sample	Oil diverted
6	0.24	surface sample	Oil broken but diverted
7	0.24	bottom sample	Oil diverted then surfaces and crosses barrier
8	0.24	mid-column	Oil successfully diverted

A second series of tests was conducted with the bubble barrier set at 30° to the flow direction to determine if the barrier would be effective in diverting neutrally buoyant oil. In this configuration, the barrier appeared to have a significant effect on the channel flow as can be seen in Figure 3. This shows the change in velocity profiles in the channel on the side away from the barrier. Experiments with this configuration are summarized in Table 2. The experiments show that the Bubble Barrier can deflect neutrally buoyant oil at water velocities of up to approximately 0.25 m/sec but any non-uniformity in the bubble curtain may lead to oil loss. In addition, the oil may be broken into a multitude of small particles even if it is successfully diverted and this could lead to additional problems in oil recovery.

CONCLUSION

Three barrier types were tested with a range of oils likely to be encountered by clean up crews after a spill of Bitumen / Diluent blend oil. None of the barriers was completely satisfactory for these unusual oils. A conventional River Boom failed to hold viscous floating oil by vortex shedding at flows of less than 0.25 m/sec. A fine mesh net successfully trapped both floating and mid-channel neutrally buoyant oil but the retention time depends on the oil viscosity. The extrusion rates are consistent with those predicted by previous studies. A bubble barrier was not successful in trapping either floating viscous oil or neutrally buoyant oil. At low water velocities the barrier was able to divert some oils but in an inconsistent manner.

These preliminary studies suggest that commonly employed barrier types need improvement to meet the requirements of spill responders for trapping heavy viscous oils and that novel design concepts should be investigated.

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THE SEPARATION OF STABLE WATER-IN-OIL EMULSIONS

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ABSTRACT

A method for the separation of stable water-in-oil emulsions into clean dischargeable water and reusable oil is being investigated. The technique involves the use of a recyclable solvent and subsequent distillation and/or membrane treatment. This method would be used as a post treatment for recovered emulsions and should significantly reduce the volume of recovered oils. This paper describes results of experiments carried out on a bench scale level.

INTRODUCTION

Stable oil-in-water emulsions are a major problem in the recovery of spilled oils. The actual amount of oil in the recovered emulsions can be as low as ten percent. These emulsions have properties that are very different from their original oils; the viscosity increases dramatically and they exhibit thixotropic properties.¹ This causes difficulties in the storage and disposal of these emulsions. Due to their chocolate brown colour and mayonnaise like consistency these special type of emulsions are called "chocolate mousse", or "mousse".

Current methods for treating "chocolate mousse" are burning or chemical demulsification. Incineration is a commonly used method for oil spill clean-up. This technology is governed by the combustibility of oil-on-water, the spreading velocity of the slick, the nature of the crude, the degree of weathering of the oil, and the oil's water content. The latter is of most interest to us, since emulsions can contain from 10% to 80% water. Emulsified oil cannot readily be ignited, and can therefore impair the burning process. A series of tests showed that a heavy crude emulsion cannot be burned with as little as a 10% water volume,

while others burned at 70% water content.² Finally this method does not permit one to collect and reuse the oil.

Chemical dispersants are employed to disperse the oil in the water column by reducing the surface tension at the oil water interface. This reduction in surface tension also inhibits the formation of emulsions. Dispersants are most effective when used to prevent the formation of emulsions. Once an emulsion has been formed the amount of surfactant needed increases by the order of a couple of magnitudes. Environment Canada specifies situations best suited for the use of surfactants.³ A few disadvantages mentioned are that: dispersants eliminate the possibility of recovering the oil; the dispersants themselves cannot be reused; the time required for the aerial-application of the chemical is much greater than that of the oil to weather and become resistant to the dispersant's effect and; there is a lack of knowledge on the fate of the volumes of dispersed oils.

Difficulties in the treatment of these "mousses" have lead Environment Canada's Emergency Engineering Division to investigate methods for the separation of "mousse" into reusable oil and clean dischargeable water. This project will investigate the separation of water-in-oil emulsions by solvent extraction, using a recyclable solvent, and membrane treatment as a wasteless process. Originally a membrane method was investigated. During the preliminary tests it became evident that the use of membranes alone would not be adequate to acquire the desired separation (due to the rheological properties of the mousse.) It was then proposed to dilute the mousse with solvent to "thin" it out. During the search for a solvent it was discovered that certain solvents alone would separate the mousse. This finding lead to the proposal of the following method.

A solvent would be used to separate the emulsion into its two phases, the oil phase and the aqueous phase. The solvent could be recovered by distillation, which could then be reused in the process.

The scope of these preliminary experiments will be limited to two artificially fabricated chocolate mousses with variable water contents. Membranes of various manufacture and pore size were tested for their efficiency in separating the mousse into oil and free water. A range of solvents were also tested for their effectiveness as emulsion separators. The recovery methods tested included distillation, gravity separation, membrane separation, both conventional and pervaporation, and the development solvent stripping apparatus. The experiments were carried out on a laboratory scale, using various test apparatus.

EXPERIMENTAL

Emulsions were prepared using an electric kitchen blender. This was done by adding simulated sea water (3.5 % NaCl in deionized water) to the oil until the desired emulsion was formed. The oils used were a mixture of weathered Alberta Sweet Mix Blend (ASMB) and bunker C (50% W/W) and California Heavy crude and ASMB (30/70 W/W). The former resulted in an emulsion of approximately 50% water while the latter was around 70%. Emulsions of up to 82% water can

be created, but this would require a more robust blender than the one provided.

The membrane separation tests were performed on two types of apparatus. The first type was a batch stirred cell. This unit required 50 mL of test material. Pressure was generated by compressed nitrogen gas, up to 100 Psi, depending on the requirements of the membrane being tested. This unit required a considerable amount of time to clean between runs, and was abandoned in favour of a syringe type of test cell (FIG 1). This test cell could contain up to 10 mL of emulsion. Various types of membranes and pore sizes were tested.

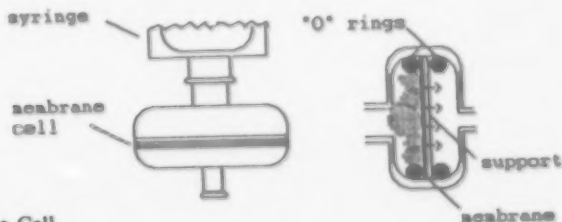


Figure 1 Membrane Cell

The apparatus used for solvent contacting is the same as that for solvent recovery. This is a simple distillation unit. It consisted of a 500mL round bottom flask, a liebig condenser, and a collection flask. In order to minimize evaporation of the solvent, a condenser was also connected to the vent. Contacting of the solvent was carried out in the round bottom flask. In order to separate the two phases the bottoms of the distillation was transferred to a separatory funnel and allowed to settle.

The solvent stripping unit was a modified distillation apparatus where by solvent vapours enter from the bottom of a condenser heated to reduce condensation of the solvent. This condenser acts as the contacting column. The emulsion enters through the top of the contacting column via a syringe. The treated emulsion is collected at the bottom of the contacting column in its two phases. The solvent vapours exit the contacting column at the top through another condenser whereby the solvent is collected for reuse in the process.

The pervaporation trials were carried out using a pervaporation unit at the National Research Council of Canada. The unit consists of a batch stirred membrane cell, condensation vessel, and a vacuum pump. Liquid nitrogen was used to condense vapours.(FIG 2) The membrane tested was a hydrophobic silicon rubber 1 mil. membrane from General Electric #1048.

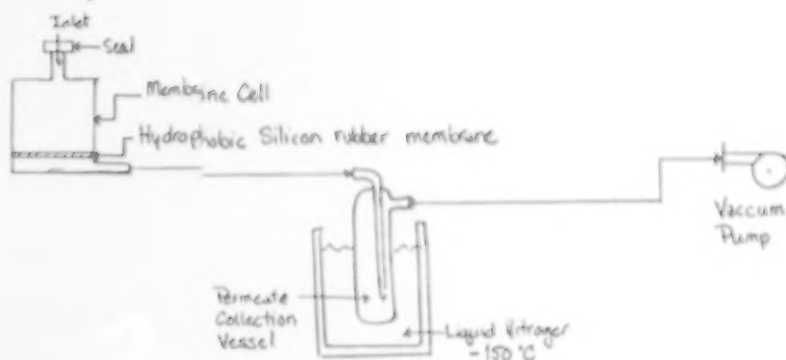


Figure 2. Pervaporation Set up

Various analytical techniques were employed for the determination of the various parameters in this study. Acetone content was determined by gas chromatography. Water content by Karl Fisher titration, and oil content by ultraviolet spectrophotometry. The first two methods were more reliable than the spectroscopy since they suffer less from matrix interferences.

RESULTS AND DISCUSSION

Direct Membrane Treatment

Direct membrane separation is a proven method that works very well for the separation of various kinds of emulsions. An attempt was made to evaluate the performance of membranes for the separation of this special type of emulsion "chocolate mousse". The membranes tested are listed in Table I along with the results.

Table 1 - Membrane separation of emulsion using CUNO Life Sciences Division (SN-charged and NU-uncharged) flat sheet nylon membranes at 200 psi, 22°C through membrane cell, emulsion was 50% water content.

Membrane Pore Size & Charge	Observations
0.1 μ C	no permeation
0.1 μ N	no permeation
0.2 μ N	no permeation
0.2 μ C	no permeation
.45 μ N	permeation no separation
.45 μ C	permeation no separation
0.8 μ N	permeation no separation
0.8 μ C	permeation no separation
1.2 μ C	permeation no separation
1.2 μ N	permeation no separation

Note: C ... charged membrane surface

N ... uncharged membrane surface

As can be seen by the results, no significant separation occurred in any of the trials. This could be due to the nature of the emulsion. Where permeation occurs the emulsion passes through the membrane as a microemulsion and does not undergo separation. When the pore size of the membrane is smaller than the size of the microemulsion the flow through the membrane is inhibited by the high viscosity of the fluid. To alleviate this, it was proposed to try to change the nature of the emulsion by the addition of solvents.

Solvent Treatment

Various solvents were tested for their effectiveness in reducing the viscosity of the emulsions. These included acetone, methyl-ethyl ketone, methyl-isobutyl ketone, dichloromethane, hexane, cresol, methanol, and isopropanol. While testing these solvents, it became apparent that the solvents alone could be used to break the emulsions.

Table 2 - Efficiencies of solvent extraction of chocolate mousse with mixing and settling methods of a 1:1 ratio of solvent to emulsion. 50% water emulsion was used.

Solvent	% of Total Oil Recovered
Acetone	> 99%
Acetone/Methanol 1:1	Separation, but not complete
Acetone/Water 2:1	98.8%
Chloroform	no separation
Dichloromethane (DCM)	85%
Freon 113	no separation
Hexane	50%
Isopar™M™	no separation
Methanol	new emulsion

The best results were for dichloromethane(DCM), and acetone. Acetone was chosen in that it is nonchlorinated, and performed significantly better than DCM.

Optimization tests were carried out to determine the best solvent to emulsion ratio. It was found that a one to one (1:1) ratio worked best.

Table 3 - Tests with different percentages of acetone. Mixing and settling method using 50% water emulsion.

% ACETONE TO EMULSION	% OF TOTAL OIL RECOVERED
10	N.A.
20	40
30	71
40	98
50	99.4
70	95

The products obtained by mixing acetone and emulsion had different characteristics depending on the amount of solvent used. At 10% acetone by weight, there was a partial destruction of the emulsion, leaving behind a thin oily phase, as well as some residual emulsion. As the amount of solvent was increased so was the total amount of emulsion destroyed and separation achieved.

This ratio was then tested on emulsions with different water contents ranging from 39% to 83%. The amount of oil recovered in all the cases did not change significantly to the amount of water present. A 50% acetone to emulsion ratio may be excessive, and further optimization experiments are required to reduce the amount of solvent utilized for such a separation.

Solvent Recovery

In order to recover the acetone for reuse it was decided to use a distillation apparatus. Two configurations were tested. The first was to mix the solvent with the emulsion, separate the two phases, and distil each phase. The second method is to mix the solvent with the emulsion, distil the mixture, and then separate the phases. The latter method was decided upon since the heating energy facilitates the solvent in separating the emulsion, and that only one distillation step is required to recover the solvent. The tops consist of mostly acetone, along with some light hydrocarbons from the oil. It is important not to use excessive heat so as to retain the lighter hydrocarbons present in the crudes. Upon separation of the bottoms, the oil phase consisted of mostly oil. The aqueous contains mostly water with some acetone and trace amounts of oil. The acetone content of the water phase ranged from 2 to 16 percent. Since acetone alone does not form an azeotrope with water⁹ the distillation should be able to remove almost all of the acetone. In reality this is not the case. The lowest concentration achieved with our system was 2% acetone in the aqueous phase. This could be due to the formation of a multiple azeotropic mixture with salt and/or trace hydrocarbons. A secondary distillation, or membrane treatment (pervaporation) may resolve this problem. It also seems beneficial to allow the aqueous phase to contain a small

percentage of acetone so that the emulsion does not reform in the distillation apparatus. The emulsion reformed only once during the distillation process, and that was the only time the solvent attained 2 percent in the aqueous phase.

The recycled solvent can be used many times. Its properties as a demulsifier deteriorate only slightly after the first cycle and then remain stable. In this study the same regenerated solvent was successfully used in all the experimental runs.

Table 4 - Results for the separation of different emulsions by distillation with acetone at a 1:1 ratio.

Water Content of Emulsion (%)	Aqueous Phase		Oily Phase		Distillate	
	% Ac	% Water	% Ac	% Water	% Ac	% Water
45.7	16.6	-	2.9	0.03	85.8	-
64.0	3.7	93.8	4.5	-	-	4.8
74.3	2.3	77.6	1.3	0.13	75.6	1.73
82.0	-	-	4.5	1.26	-	-

Solvent Vapour Stripping

Another method that was looked into was the use of a counter current solvent stripping apparatus. This set up would allow the use of a continuous mode of operation, whereby the solvent could be used recycled in a closed loop, and the emulsion would flow through the system (FIG 3). When the emulsion contacted the solvent vapour, an immediate change occurred. The emulsion became dark on the perimeter and water droplets emerged. The set up used was very crude and did not have adequate insulation or contacting surface. Even though, the results obtained warrant further study. The mass of the recovered oil was equal to the oil portion of the emulsion treated. The same was found for the water portion. This method showed promise and will be studied further.

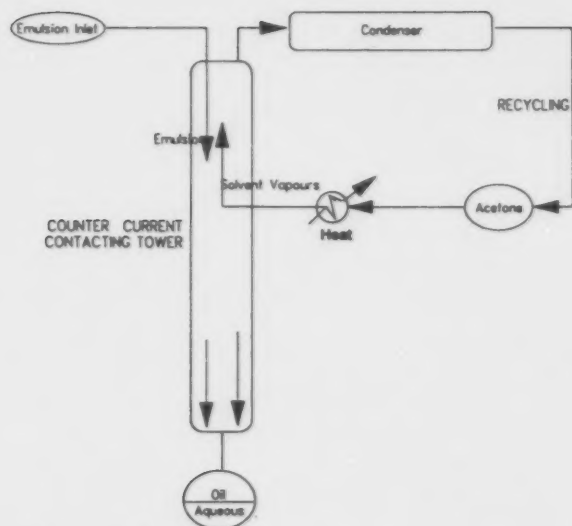


Figure 3. Solvent Vapour Stripping

Post Treatment of the Produced Water

Membrane Liquid Separation

Post treatment of the produced water included direct membrane separation and pervaporation. Membrane separation was only capable of removing on average 50% of the dispersed oil in the collected aqueous phase. It is shown in Table 5 that all the membranes tested, from UF to NF, were equally effective in the retention of the larger oil droplets. Since 40 to 60 percent of the oil remaining in the aqueous phase is present in a dissolved form it can not be retained by MF, UF, or even NF membranes. The rest of the oil is present in the form of suspended droplets (oil-in-water emulsion). This emulsion can readily be rejected by all of these membranes.

Pervaporation

To improve the process water quality, and to recover acetone from this mixture, pervaporation trials were carried out. A hydrophobic silicone rubber membrane was used in this series of experiments. The pressure on the permeate side was varied between 5 and 11 mm Hg. The temperature ranged between 20 and 50 C. Results showed that the acetone preferably passed through the membrane so that the acetone concentration in the permeate was 3 to 4 times higher than in the starting aqueous phase. It was found that by increasing the temperature, the permeate flux might be increased sufficiently without compromising the quality of the separation.

Table 5 - Post-Treatment to Remove Oil from the Aqueous Phase with Different Membrane Systems. Only the Desal5 run was done in the Stainless Steel Stirrer Cell.

Membrane Type	t (°C)	P (psi)	Perm Flow-rate (L/m ² *hr)	Perm Conc. of oil (ppm)	% R of Oil
Amicon YM 30K	24	40	300	36.92	50.2
Amicon YM 100K	24	40	900	37.44	49.5
Bioken 10K	25	40	340	19.06	57.1
Bioken 30K	25	40	320	25.75	42.0
Bioken 100K	25	40	630	27.54	62.8
Cuno 0.8 μ NU	25	20	720	21.26	52.2
Cuno 0.8 μ SN	25	20	830	25.33	43.0
Cuno 1.2 μ NU	24	40	4800	29.93	67.3
Cuno 1.2 μ SN	24	40	5480	81.39	11.2
Filtron Modified	25	40	3190	45.56	69.5
Filtron Omega 30K	25	40	510	34.74	76.7
Desal 5 NF Hydrophilized	27	100	7	78.43	53.5

CONCLUSIONS

The results of these preliminary tests show that stable water-in-oil emulsions can be separated quite readily with a regenerated solvent system. The only products of these systems are oil, which can be sent to a refinery, and dischargeable water. The recycled solvent can be used many times with out any significant decrease in separation efficiency. In order to enhance the throughput of the system a solvent vapour stripping method was invented. This solvent vapour stripping also improves the quality of the products and the recycled solvent. Membrane methods can be used as a post treatment for the produced water in order to better comply with discharge limits.

ACKNOWLEDGEMENTS

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Oil Spill Sorbents: Testing Protocol and Certification Listing Program

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INTRODUCTION

A universally accepted standard method for testing oil spill sorbents is not currently employed by the majority of sorbent manufacturers. End-users are limited to manufacturers' and distributors' claims which may be perceived as being biased. Environment Canada has spearheaded a drive to develop an official Canadian standard for the testing and certification of sorbents using the Canadian General Standards Board (CGSB) as the certification body. It is anticipated that Environment Canada will provide a system to maintain an unprejudiced method for testing oil spill sorbents.

BACKGROUND

Environment Canada's Emergencies Engineering Division (EED) is mandated to evaluate existing technologies and act as a proving ground for technologies deemed new and innovative in areas of Oil and Chemical Spill Cleanup. The sorbent testing program had its beginnings in 1974 when Environment Canada released its first publication entitled "Selection Criteria and Laboratory Evaluation of Oil Spill Sorbents". Updates to this publication were release every four or five years. The time lag between publications and the limited number of sorbents tested were acceptable limitations to this program as interest in sorbents was relatively limited. Since that time; however, interest in sorbent performance evaluation has grown steadily. Recent events including the Exxon Valdez spill in Prince William Sound and the spills during the Gulf War spurred renewed interest in sorbents.

Manufacturers and Distributors were aggressively marketing their products to Government, Oil Spill Co-ops, and other Non-Government Organizations (NGOs). These end-users had limited third party data from which they could base a purchasing decision. First Responders, sceptical of the performance and safety aspects associated with some sorbents, requested that sorbents pass some sort of approval mechanism before being considered. It was this demand for an approval mechanism that catalyzed the development of the sorbent evaluation and certification program.

PROGRAM DEVELOPMENT

As requests for sorbent performance information grew, it became obvious that an ongoing evaluation system was warranted. Requests for "approving" or "certifying" sorbents could not be met simply because such a mechanism did not exist. At this point EED began talks with the Canadian General Standards Board (CGSB). This Federal Government Agency is one of only five National Standardizing bodies in Canada. A committee was formed through the CGSB consisting of equal representation from interested parties, producers, and end-users throughout North America. This led to the development of a new test procedure based upon work Environment Canada had performed in the past¹, but also incorporating methods from the American Society for Testing and Materials (ASTM)². These protocols currently enjoy top status as sorbent test protocols in North America.

CGSB SORBENT CERTIFICATION AND LISTING PROGRAM

The CGSB Sorbent Certification and Listing Program currently consists of two documents. One is a standard for sorbent materials, while the other specifically defines testing procedures for sorbents used on crude oil and similar spills. The program is structured in this fashion to allow the introduction of additional testing protocols. One anticipated protocol will deal specifically with testing sorbents for use with aggressive chemicals.

Standard C**/CGSB-183.1 encompasses "Sorbent Materials" and relates to operational and performance criteria for the clean-up and control of oil and hazardous substances spills. It is within the "Sorbent Materials" document that testing protocol terms and calculations are explicitly defined. Sorbents are classified by physical type based on ASTM F726-81 (1986) as follows:

- Type I: sheet, pad, blanket, mat
- Type II: loose - unconsolidated, particulate material
- Type IIIa: pillows and socks - sorbent material contained by an outer fabric or netting.
- Type IIIb: booms - sorbent material contained by outer fabric or netting which has a lengthwise dimension exceeding other dimensions by a factor of at least five and whose sorption capacity would be significantly altered if cut to meet Type I size requirements.

Type IIIc: sweeps

Type IV: agglomerated unit - pom pom, yarn, or netting which offer low impedance to highly viscous fluids.

An Interim Standard is now in place, but is limited to testing Type I and Type II sorbents. It is anticipated that testing protocols for remaining Types will be incorporated into the official Standard during the fourth quarter of 1992.

Sorbents are also classified by category which determines the recommended type of application as follows:

- | | |
|---------------|--|
| L-W category: | sorbents which are recommended for sorbing spills on water or land. |
| L category: | sorbents which are recommended for sorbing spills exclusively on land. |
| W category: | sorbents which are recommended for sorbing spills exclusively on water. |
| I-S category: | sorbents which are recommended for sorbing spills in an industrial setting (aggressive chemicals). |
| ALTERNATE: | encompass all sorbents which technically fail tests, but possess at least one redeeming characteristic which warrants further consideration. |

The Sorbent Materials Standard goes on to identify nine sorbent characteristics which should be considered. Specific labelling and Material Safety Data Sheets are a requirement, as are sturdy storage properties.

Testing Procedure

Standard C**/CGSB-183.2 covers laboratory conducted performance tests for all forms of sorbent materials, regardless of their mode of action, for the sorption of crude oil, its contained natural components, and mixtures thereof.

Performance Characteristics

Specific characteristics were initially identified as being highly desirable. They are as follows:

- **Buoyancy:** Data obtained would allow confirmation that a particular sorbent may be suited for use in a spill on water. Sorbents that sink may pose a threat to aquatic life by transporting hazardous liquids to the sediment causing infiltration into the entire food chain.
- **Low Water Pick-up:** Non-selective sorbents may pick up water in addition to oil if placed in an aquatic environment. This may not prove to be a major

hindrance if the sorbent remains floating; however, any water sorbed would displace the spilled oil, thus hindering performance.

- **High Oil Pick-up:** The rate of pick-up in addition to the sorbent's capacity would be tested. A sorbent's ability to be "self acting" could limit the application to specific spill scenarios.
- **Reuse:** Some sorbents allow the sorbed liquid to be extracted via mechanical or chemical means enabling reuse. This could limit the amount of solid waste generated during a spill cleanup operation. Safety aspects of attempting reuse should be carefully considered.
- **Low Rate of Release:** Liquids sorbed by most sorbents are released back into the environment to some degree. The extent of release will vary dramatically depending upon the sorbent used. The importance of this release depends upon the specific spill scenario, and storage equipment available at the spill site.

Test Method

The following tests have been established to evaluate the performance of sorbents on oil and water. The procedures followed are condensed versions of the test methods outlined by the Canadian General Standards Board.

Degradation Pre-Test (Static): This test measures the sorbent's hydrophobic characteristics in addition to determining buoyancy of a sorbent. A test cell (crystallizing dish having a diameter of 190 mm) is filled with a layer of water approximately 80 mm deep. If Type II sorbent is being tested, a mesh basket having openings of approximately 1 mm is lowered into the crystallizing dish. The sorbent sample (Type I: 13 cm x 13 cm, Type II: 10 grams) is placed into the cell. The test cell is then covered and left for 15 minutes. After 15 minutes the sorbent is removed from the water and observations are noted. The sorbent is weighed to determine water pick-up. Samples that pass are then prepared for the Degradation Test (Static).

Degradation Pre-Test (Dynamic): This test is used to determine the buoyancy of sorbents in simulated wave conditions. If the sorbent passes this test for buoyancy, it is then very unlikely that the sorbent will sink in most applications. Sample pieces of the sorbent (Type I: 16 pieces of 3 cm x 3 cm, Type II: 3-5 grams) are placed in a 2 litre jar which is half filled with water. The container is then placed on its side and mounted on a shaker table set at a frequency of 10 cycles per minute for a duration of 15 minutes. The sorbent is then removed from the water and observations are noted. The sorbent is weighed to determine water pick-up.

Degradation Test (Static): This is a test for buoyancy, sorbent capacity, and oil retention. A sorbent sample from the static pre-test is placed on a 5 mm layer of crude oil floating on an 80 mm layer of water. The sample is left undisturbed for a period of at least 48 hours. The sorbent is then removed and hung from a balance (Type I: hung vertically using a clip, Type II: hung horizontally using a basket). Observations pertaining to the physical condition of the sorbent are recorded. The weight of the sorbent is measured as oil drips after 15 seconds, 30 seconds, 1 minute,

2 minutes, 5 minutes, and 30 minutes. A retention profile is obtained from this data, as is the sorbent's capacity. Mechanical compression is used to extract remaining liquid from the sorbent in order to determine water pick-up.

Degradation Test (Dynamic): This test follows the methodology of the Degradation Pre-Test (Dynamic) with the exception that 150 ml of crude oil is introduced into the 2 L jar. Observations of the sorbent's behaviour during agitation are recorded. After 15 minutes the sorbent is removed and weighed to determine oil pick-up. Mechanical compression is used to extract liquid from the sorbent to determine water pick-up for comparison with the static test.

L-W Category Test: This is a test for sorbent capacity and reuse. A fresh sorbent sample is placed on a 5 mm layer of crude oil floating on an 80 mm layer of water. The sample is left for a period of 15 minutes. The sorbent is then removed and left to drip for 30 seconds before being weighed (Type I: hung by clip, Type II: hung by basket). Observations pertaining to the physical conditions of the sorbent are recorded. Mechanical compression is used to extract remaining liquid from the sorbent for reuse testing and water content determination. The data is also compared with Degradation Test (Static) results.

L Category Test: This is a test for sorbent capacity, reuse and retention. A fresh sorbent sample is placed on a 7.5 mm layer of crude oil. The sample is left for a period of 15 minutes. The sorbent is then removed and hung from a balance (Type I: hung vertically using a clip, Type II: hung horizontally using a basket). Observations pertaining to the physical condition of the sorbent are recorded. The weight of the sorbent is measured as oil drips after 15 seconds, 30 seconds, 1 minute, 2 minutes, 5 minutes, and 30 minutes. A retention profile is obtained from this data, as is the sorbent's capacity. Mechanical compression is used to extract remaining liquid from the sorbent for reuse testing.

W Category: Data obtained from the L-W test and the Degradation Test (Dynamic) will determine if a sorbent should be designated for the W Category. A sorbent requiring agitation would not be recommended for use on land thus may fall into the W Category.

I-S Category Test: This testing procedure is currently under review.

Non Performance - Handling

This information is provided by the manufacturer for the benefit of the end-user, but is not a requirement for certification.

- **Tensile Strength:** This characteristic becomes extremely important when dealing with sorbent booms. This characteristic determines the ability of a boom to retain its integrity under the strain of currents and wave action.
- **Storage:** Ideally, a sorbent would occupy a minimum of storage space, while

exhibiting a high sorption capacity. Storage space within facilities is often very limited.

- Disposal: Proper and safe disposal methods should be addressed before application of any sorbent to a spill. Regulations may limit options.
- Static Resistance: In very dry conditions (desert or arctic) static resistance becomes an important safety concern. Specific conditions would have to be met before a static spark could ignite a flammable liquid. Steps should be taken to ensure safe working practices are enforced and working environments should be carefully scrutinized for ALL possible sources of static charge.

FUTURE AREAS OF DEVELOPMENT

Test liquids used in the Interim Standard represent a cross-section of viscosities for oil were chosen based upon suitability and availability. It is the intention of the CGSB General Sorbent Committee to expand upon this list to encompass hazardous liquids which are frequently spilled during transportation and in industrial settings. It is also the intention of the committee to expand into the area of sorbent boom testing.

CONCLUSIONS

This program should benefit both manufacturers and users. Manufacturers will be given the opportunity to have their products tested by impartial third party laboratories and certified to that effect. Users will be able to select products from manufacturers and compare data objectively. The reader should note that this program is prototype in nature. EED hopes to expand this type of program to encompass booms, skimmers, and related spill response equipment. A centralized database of performance and non-performance data pertaining to oil and hazardous liquid spills is the long-term goal.

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APPENDIX A

C**/CGSB-183.2

CANADIAN GENERAL STANDARDS BOARD

Draft Method for Testing Sorbents

1. SCOPE

- 1.1 This method covers laboratory-conducted performance tests for all forms of sorbent materials, regardless of their mode of action, for the sorption of crude oil, its contained natural components and mixtures thereof.
- 1.2 The testing and evaluation of a product against this standard may require the use of materials and/or equipment that could be hazardous. This document does not purport to address all the safety aspects associated with its use. Anyone using this standard has the responsibility to consult the appropriate health and safety practices in conjunction with any existing applicable regulatory requirements prior to its use.

2. APPLICABLE PUBLICATIONS

- 2.1 The following publications are applicable to this method
 - 2.1.1 Canadian General Standards Board
25-GP-1M Method 44.1,
 - 2.1.2 Environment Canada
A Catalogue of Crude Oil and Oil Product Properties, 1990 EETD.
- 2.2 Reference to the above publications and to other standards is to the latest issues unless otherwise specified by the authority applying this standard. The sources for the publications are shown in the Notes Section 13.

3. PRINCIPLE

- 3.1 The sorbent materials are tested using established tests for factors relating to performance and handling.

4. SIGNIFICANCE AND USE

This method is to be used as a basis for comparison of sorbents in a consistent manner and to present their characteristics and properties of value during their lifecycle. The sorbents shall be classified in the following types and categories.

4.1 Types

- 4.1.1 Type I: sheet, pad, blanket.
- 4.1.2 Type II: loose - unconsolidated, particulate material.
- 4.1.3 Type III: enclosed
 - Type III Series A: pillows and socks - sorbent material contained by an outer fabric or netting.
 - Type III Series B: booms - sorbent material contained by outer fabric or

netting which has a lengthwise dimension exceeding other dimensions by a factor of at least five and whose sorption capacity would be significantly altered if cut to meet Type I size requirements.

Type III Series C: sweeps

- 4.1.4 Type IV: agglomerated unit - pom pom, yarn, or netting which offer low impedance to highly viscous fluids.

4.2 Categories

- 4.2.1 The L-W category refers to sorbents which are recommended for sorbing spills on land or water.
- 4.2.2 The L category refers to sorbents which are recommended for sorbing spills exclusively on land.
- 4.2.3 The I-S category refers to sorbents which are recommended for sorbing spills in an industrial setting.
- 4.2.4 The W category refers to sorbents which are recommended for sorbing spills on water only.
- 4.2.5 The ALTERNATE category will encompass sorbents which do not meet the requirements of the above categories but possess at least one redeeming characteristic which warrants further consideration.

5. APPARATUS AND MATERIALS

- 5.1 Test Cells (open): The dimensions of the test cells shall be of a large enough size to enable sorbent sample to float freely within the test basket. The following is a recommended vessel for Type I and Type II sorbents: Pyrex 190 mm (diameter) X 100 mm (depth) crystallizing dish with a watch glass or glass plate cover to accommodate a sample size not less than 130 mm (L) by 130 (W) or 6 grams. Type IIIa, Type IIIb, and Type IV may require larger cells to accommodate the sorbent sample dimensions.
- 5.2 Test Cells (enclosed): Test cells for use with shaker table should be large enough to enable wave action to thoroughly mix water and test liquid with sorbent. A 4L glass jar with a screw type lid is recommended.
- 5.3 Basket for Type II test: The basket shall be of a sufficient size and strength to accommodate the sample size and weight when saturated. A stainless steel basket having 1.5 mm¹ openings is recommended. The basket must not be so tall as to interfere with the lid.
- 5.4 Basket type IIIa, IIIb, IV test: The basket shall be of sufficient size and strength to accommodate the sample size and weight when saturated. A stainless steel mesh having 5 mm openings is recommended.

¹ The mesh should retain the sorbent, yet allow free oil to drain away from the sorbent.

- 5.5 Cold room or ice-cooled bath or equivalent to maintain a temperature of 15°C.
- 5.6 Top Loading Balance: 0.01 g resolution. A range of up to 400 g is recommended for sorbents of Type I, Type II. A higher upper limit may be necessary for Type IIIa, Type IIIb and Type IV configurations.
- 5.7 20 cm diameter weighing pans (non-stick coated pan or lined pan recommended for ease in cleaning).
- 5.8 Wringer-type Press: Hand operated with a double roller design not dissimilar to wringer-type washing machines. Tension to rollers should approximate 200 Newtons (45 lb) (eg. 20 kg weight).
- 5.9 Plate Press: Hydraulic press or similar device able to apply 1000 Newtons (224 lb) of force (eg. 100 kg weight) on top plate measuring 15 cm x 15 cm.
- 5.10 Graduated Conical Centrifuge Tubes (100 ml capacity).
- 5.11 Shaker table capable of producing a frequency of 150 cycles/min and an amplitude of 3 cm (Eberbach Shaker Table or equivalent).

6. TEST LIQUIDS

- 6.1 The types of fluids to be tested should be representative of the wide variety of fluids that sorbents could be used to clean up. The testing will be restricted to the following liquids.

- 6.1.1 Diesel Fuel Oil Grade 2-D, Automotive diesel fuel oil
API GRAVITY: 39.4 (EETD 84) (15/15°C)
DENSITY: 0.827 g/ml @ 15°C (EETD 85) DYN. VISCOSITY: 2.7 cP @ 15°C (EETD 85)
- 6.1.2 Crude Oil Alberta Sweet Mixed Blend
API GRAVITY: 37.0 (EETD 84) (15/15°C)
DENSITY: 0.839 g/ml @ 15°C (EETC 84) DYN. VISCOSITY: 9.2 cP @ 15°C (EETD 85)
- 6.1.3 Weathered Crude Alberta Sweet Mixed Blend (7 day weathered-25% volumetric loss)
DENSITY: 0.883 g/ml @ 15°C (EETD 84) DYN. VISCOSITY: 48 cP @ 15°C (EETD 85)
- 6.1.4 Fuel Oil #6 Bunker C Fuel Oil (Fuel Oil Number 6)
API GRAVITY 12.3 (EETD 88) (15/15°C)
DENSITY: 0.974 g/ml @ 15°C (EETD 84) DYN. VISCOSITY: 48,000 cP @ 15°C (EETD 88)

Care must be taken when dealing with volatile liquids to ensure excessive evaporation does not occur.

7. **CONDITIONING**

- 7.1 Sorbents shall be inspected upon receipt by the testing agency and damaged specimens shall be removed and placed as needed.
- 7.2 Condition all sorbent test specimens at $20 \pm 3^{\circ}\text{C}$ and $60 \pm 5\%$ relative humidity for not less than 24 h prior to testing. Condition specimens in a fully exposed state with no coverings or wrapping that would hinder the ambient equilibration process.

8. **NON-PERFORMANCE HANDLING**

- 8.1 Storage
- 8.2 Disposal

9. PROCEDURE

- 9.1 **Static Water Test:** This procedure is designed to test for water pick-up under stagnant conditions. This test is performed at room temperature.
- 9.1.1 **Type I Sorbent:** The test cell is filled with a layer of water (80 mm). Approximately 130 mm x 130 mm square of a weighed sorbent sample is lowered into the test cell. The sorbent should float freely on the water. Place a lid on the cell to prevent evaporation and to protect the cell. After 15 minutes (± 20 sec) check the condition of the sorbent. If the sample sinks go directly to step 9.5, otherwise remove the sorbent vertically with a clip and let drain hanging over the cell for 30 seconds (± 3 sec). Place a tared weighing pan under the sorbent to catch any additional drips and immediately transfer the sorbent to the pan. Determine and record the sample weight. Retain the sorbent sample for use in the Static Long Term Sorption test. All tests are triplicated with the median of the three runs being used for calculations. If the value of any run (g/g) deviates by more than 15 % from the mean of the three runs, then the samples shall be rejected and the test repeated with three new specimens.
- 9.1.2 **Type II Sorbent:** The test cell is filled with a layer of water (80mm). A sorbent sample of approximately 200 ml is weighed then placed in a basket which is lowered into the test cell. The sorbent should float freely on the water. Place a lid on the cell to prevent evaporation and to protect the cell. After 15 minutes (± 20 sec) check the condition of the sorbent. If the sample sinks go directly to step 9.5, otherwise remove the sorbent with the basket and let drain over the cell for 30 seconds (± 3 sec). Place the basket over a tared weighing pan to catch any additional drips and immediately transfer the sorbent to the pan. Record the weight. Retain the sorbent sample for use in the Static Long Term Sorption test. All tests are triplicated with the median of the three runs being used for calculations. If the value of any run (g/g) deviates by more than 15 % from the mean of the three runs, then the samples shall be rejected and the test repeated with three new specimens.
- 9.1.3 **Type IIIa Sorbent:** *Not available at this time*
- 9.1.4 **Type IIIb Sorbent:** *Not available at this time*
- 9.1.5 **Type IV Sorbent:** *Not available at this time*
- 9.2 **Long Term Static Sorption test:** This procedure is designed to test for oil pick-up and determine hydrophobic properties of a sorbent sample. This test is performed at 15°C.
- 9.2.1 **Type I Sorbent:** Lower the wetted sample from the Static Water Test with a clip on a 5 mm layer of crude oil on excess water bath (80 mm or more) at 15°C. After a minimum of 24 hours check the condition of the sorbent. If the sample sinks go directly to step 9.5, otherwise remove the sorbent vertically with the clip and immediately hang from the balance. Place a tared

weighing pan under the hanging basket to catch any drips. Record the weight of the saturated sorbent at 30 seconds, 45 seconds, 1 minute, 2 minutes, 5 minutes, 15 minutes and 30 minutes. At the 30 minute mark transfer the sorbent to the pan. Transfer the sample and any residual liquid that remains in the pan to the wringer press and squeeze the sorbent through the press five times. Collect liquid in a graduated conical centrifuge tube for water content determination. If the meniscus is distinctly visible in the conical tube then water content may be read directly. Reweigh the pressed sorbent and record the value. If the meniscus is not distinctly visible, the emulsion may be broken by adding a small quantity of toluene to the centrifuge tube (approximately 10-20 ml). Observations should include but not be limited to: buoyancy, disintegration, and appearance. The sorbent must remain structurally sound at saturation while being held along a side (avoid hanging by corner) of the sample and must not sink. All tests are triplicated with the median of the three runs being used for calculations. If the value of any run (g/g) deviates by more than 15 % from the mean of the three runs, then the samples shall be rejected and the test repeated with three new specimens.

- 9.2.2 Type II Sorbent: Lower the basket containing the wetted sample from the Static Water Test on a 5 mm layer of crude oil on excess water bath (80 mm or more) at 15°C. After a minimum of 24 hours check the condition of the sorbent. If the sample sinks go directly to step 9.5, otherwise remove the sorbent with the basket and immediately hang the basket from the balance. Place a tared weighing pan under the hanging basket to catch any drips. Record the weight of the basket with the saturated sorbent at 30 seconds, 45 seconds, 1 minute, 2 minutes, 5 minutes, 15 minutes and 30 minutes. At the 30 minute mark transfer the sorbent to the pan. Determine and record the sample weight. Weigh the empty basket for future calculations. Transfer the sample and any residual liquid that remains in the pan to the plate press and squeeze the sorbent with 1000 Newtons of force (224 lb). This action may be cycled up to five times to extract remaining oil. Collect liquid in a graduated conical centrifuge tube for water content determination. If the meniscus is distinctly visible in the conical tube then water content may be read directly. Reweigh the pressed sorbent and record the value. If the meniscus is not distinctly visible, the emulsion may be broken by adding a small quantity of toluene to the centrifuge tube (approximately 10-20 ml). Observations should include but not be limited to: buoyancy, disintegration, and appearance. The sorbent must not sink. All tests are triplicated with the median of the three runs being used for calculations. If the value of any run (g/g) deviates by more than 15 % from the mean of the three runs, then the samples shall be rejected and the test repeated with three new specimens.

9.2.3 Type IIIa Sorbent: *Not available at this time*

9.2.4 Type IIIb Sorbent: *Not available at this time*

9.2.5 Type IV Sorbent: *Not available at this time*

- 9.3 **Dynamic Test:** This procedure is designed to test for water pick-up and to determine oleophilic properties of a sorbent sample under dynamic conditions. This test is performed at room temperature.
- 9.3.1 Sample pieces of the sorbent (Type I: 4 pieces of 6 cm x 6 cm, Type II: 200 ml) are placed in a 4 litre jar which is half filled with water and sealed. The container is then placed on it's side and mounted on a shaker table set at a frequency of 150 cycles per minute and an amplitude of 3 cm for a duration of 15 minutes. If the sample sinks go directly to step 9.5, otherwise remove the sorbent by straining the contents of the jar through a mesh basket to catch the sorbent. The jar is half filled with fresh water and 10 ml of crude oil is added. The sorbent sample is returned to the jar which is then sealed. The container is placed on it's side and mounted on a shaker table set at a frequency of 150 cycles per minute and an amplitude of 3 cm for a duration of 15 minutes. The jar is allowed to settle for a period of 2 minutes, at which time observations are recorded. Observations include but are not limited to: quantity of sorbent submerged, physical appearance of sorbent, and persistence of oil sheen.
- 9.4 **L-W test:** This procedure will determine the amount of test liquid that a sorbent will pick up in 15 minutes. Fresh samples are used for this test which is performed at 15°C.
- 9.4.1 **Type I Sorbent:** The sorbent to be tested should be cut with a sharp edge to minimum dimensions of 130 mm x 130 mm square. The sorbent is then weighed and the value is recorded. The test cell is filled with an initial layer of water (80 mm or more) and a quantity of test liquid to produce the required thickness for the test. The required thickness for diesel fuel is 2.5 mm, while 5 mm is required for crude oil, bunker C, and weathered crude oil. The sorbent is lowered into the cell. The sorbent should float freely on the test liquid. Place a lid on the cell to prevent evaporation and to protect the cell. After 15 minutes $\pm$ 20 seconds (sorbent should be flipped at 8 minute mark) remove the sorbent with a clip and let drain hanging over the cell for 30 seconds ($\pm$ 3 sec). Place a tared weighing pan under the sorbent sample to catch any additional drips and immediately transfer the sorbent to the pan. Determine and record the sample weight. Transfer sample and any residual liquid that remains in the pan to the wringer press and squeeze the sorbent through the press five times. Reweigh the pressed sorbent and record the sample weight. Collect liquid in a graduated conical centrifuge tube for water content determination. If the meniscus is not distinctly visible, the emulsion may be broken by adding a small quantity of toluene to the centrifuge tube (approximately 10-20 ml). Each sorbent sample shall be tested through five complete sorption cycles or until it's sorbency is reduced to 50% of its initial value or until disintegration. Sorbents will be classified as High Reuse (5 cycles), Medium Reuse (3 or 4 cycles), Low Reuse (1 or 2 cycles), or No Reuse. All tests are triplicated with the median of the three runs being used for calculations. If the value of any run deviates by more

than 15 % from the mean of the three runs, then the samples shall be rejected and the test repeated with three new specimens.

- 9.4.2 **Type II Sorbent:** The sample size of the sorbent to be tested should be approximately 200 ml. The sorbent is weighed and the value is recorded. The test cell is filled with an initial layer of water (80 mm or more) and a quantity of test liquid to produce the required thickness for the test. The required thickness for diesel fuel is 2.5 mm, while 5 mm is required for crude oil, bunker C, and weathered crude oil. The sorbent is placed in a basket which is then lowered into the cell. The sorbent should float freely on the test liquid. Place a lid on the cell to prevent evaporation and to protect the cell. After 15 minutes $\pm$ 20 seconds remove the sorbent with the basket and let drain over the cell for 30 seconds ($\pm$ 3 sec). Place a tared weighing pan under the sorbent sample to catch any additional drips and immediately transfer the sorbent to the pan. Determine and record the sample weight. Weigh the empty basket for future calculations. Transfer the sample and any residual liquid that remains in the pan to the plate press and squeeze the sorbent with 1000 Newtons of force. This action may be cycled up to five times to extract remaining oil. Collect liquid in a graduated conical centrifuge tube for water content determination. Reweigh the pressed sorbent and record the sample weight. If the meniscus is not distinctly visible, the emulsion may be broken by adding a small quantity of toluene to the centrifuge tube (approximately 10-20 ml). All tests are triplicated with the median of the three runs being used for calculations. If the value of any run deviates by more than 15 % from the mean of the three runs, then the samples shall be rejected and the test repeated with three new specimens.

9.4.3 **Type IIIa Sorbents:** *Not available at this time*

9.4.4 **Type IIIb Sorbents:** *Not available at this time*

9.4.5 **Type IV Sorbents:** *Not available at this time*

- 9.5 **L Test:** This procedure will test the amount of pure test liquid that a sorbent can pick up in 15 minutes. Fresh samples are used for this test which is performed at 15°C.

- 9.5.1 **Type I Sorbent:** The sorbent to be tested should be cut with a sharp edge to minimum dimensions of 130 mm x 130 mm square. The sorbent is then weighed and the value is recorded. The test cell is filled with an initial layer of test liquid. The required thickness for all test liquids is 7.5 mm. The sorbent is lowered into the cell. The sorbent should float freely on the test liquid. Place a lid on the cell to prevent evaporation and to protect the cell. After 15 minutes $\pm$ 20 seconds (sorbent should be flipped at 8 minute mark) remove the sorbent vertically with a clip and let drain hanging over the cell for 30 seconds $\pm$ 3 seconds. Place a tared weighing pan under the sorbent sample to catch any additional drips and immediately transfer the sorbent to the pan. Determine and record the sample weight. Transfer sample and any

residual oil that remains in the pan to the wringer press and squeeze the sorbent through the press five times. Reweigh the pressed sorbent to determine and record the sample weight. Each sorbent sample should be tested through five cycles or until its sorbency is reduced to 50% of its initial value or until disintegration. Sorbents will be classified as High Reuse (5 cycles), Medium Reuse (3 or 4 cycles), low reuse (1 or 2 cycles), or No Reuse. All tests are triplicated with the median of the three runs being used for calculations. If the value of any run deviates by more than 15 % from the mean of the three runs, then the samples shall be rejected and the test repeated with three new specimens.

- 9.5.2 **Type II Sorbent:** The sample size of the sorbent to be tested should be approximately 200 ml. The sorbent is weighed and the value is recorded. The test cell is filled with an initial layer of test liquid. The required thickness for all test liquids is 7.5 mm. The sorbent is placed in a basket which is then lowered into the cell. The sorbent should float freely on the test liquid. Place a lid on the cell to prevent evaporation and to protect the cell. After 15 minutes $\pm$ 20 seconds remove the sorbent with the basket and let drain over the cell for 30 seconds ($\pm$ 3 sec). Place a tared weighing pan under the sorbent sample to catch any additional drips and immediately transfer the sorbent to the pan. Determine and record the sample weight. Weigh the empty basket for future calculations. Transfer the sample and any residual liquid that remains in the pan to the plate press and squeeze the sorbent with 1000 Newtons of force. This action may be cycled up to five times to extract remaining oil. Reweigh the pressed sorbent to determine and record the sample weight. Each sorbent sample should be tested through five cycles or until its sorbency is reduced to 50% of its initial value or until disintegration. Sorbents will be classified as High Reuse (5 cycles), Medium Reuse (3 or 4 cycles), low reuse (1 or 2 cycles), or No Reuse. All tests are triplicated with the median of the three runs being used for calculations. If the value of any run deviates by more than 15 % from the mean of the three runs, then the samples shall be rejected and the test repeated with three new specimens.

9.5.3 **Type IIIa Sorbents:** *Not available at this time*

9.5.4 **Type IIIb Sorbents:** *Not available at this time*

9.5.5 **Type IV Sorbents:** *Not available at this time*

9.6 **I-S Test:** *not available at this time*

10. **CALCULATIONS** - Using data from section 9 calculate the following:

- 10.1 **Static Water Test:** Use values obtained in 9.1 and static value of water uptake as grams water per gram of sorbent.
- 10.2 **Long Term Static Sorption Test:** Use values obtained in 9.2 and static value of test fluid sorbed as grams of test liquid per gram of sorbent and static value of water uptake as grams water per gram of sorbent. Calculate and display

water percentage of total uptake. Calculate and draw profile of retention (curve) from values obtained at 30 sec, 45 sec, 1 min, 2 min, 5 min, 15 min, 30 min.

- 10.3 **Dynamic Test:** No calculations required - observations are recorded.
- 10.4 **L-W Test:** Use values obtained in 9.4 and state value of test fluid sorbed as grams of test liquid per gram of sorbent. (Volume of test liquid per gram of sorbent should also be calculated and recorded). Use values obtained in 9.3 and state value of water sorbed as grams of water per gram of sorbent. Calculate and display water percentage of total uptake. Determine reuse potential for each test liquid.
- 10.5 **L Test:** Use values obtained in 9.5 and state value of test fluid sorbed as grams of test liquid per gram of sorbent. (Volume of test liquid per gram of sorbent should also be calculated and recorded). Determine reuse potential for each test liquid.
- 10.6 **L-S Test:** *Not available at this time*
- 10.6 **Reaction Time:** A quantitative comparison will be made between long term sorption in 9.2 and the crude oil uptake in section 9.4. Any sorbent that has not reached 92% saturation by the 15 minute mark will be designated as a slow sorbent. (Assuming sorbents reach saturation within 24 hours).
- 10.7 **Storage Density:** The storage density is calculated ($\text{kg sorbent}/\text{m}^3$) based on manufacturer's packaging.

11. **ADDITIONAL TESTS**

- 11.1 An additional specialized test method may be employed by the authority having jurisdiction if these test methods are shown to severely hamper a sorbents performance.

12. **REPORT**

Data acquisition format - currently under review

13 **NOTES**

- 13.1 **Related Publications**
ASTM

Environment Canada

F726-81 Sorbent Performance of Adsorbents
F716-82 Sorbent Performance of Absorbents
Selection Criteria and Laboratory Evaluation of
Oil Spill Sorbents, an Update, Update II,
Update III, Update IV.

- 13.2 The publications referred to in par. 2.1.1 may be obtained from the Canadian General Standards Board, Sales Unit, Ottawa, Canada, K1A 1G6. Telephone (819) 956-0425 or 956-0426.
- 13.3 The ASTM publications referred to in par 13.1 may be obtained from ASTM, 1916 Race Street, Philadelphia, PA 19103, U.S.A. or from the Standards Council of Canada, Standards Sales Branch, 350 Sparks Street, Suite 1200, Ottawa, Ontario K1P 6N7.

REFERENCES

1. S.L. Ross Environmental Research Limited for Environment Canada, Selection Criteria and Laboratory Evaluation of Oil Spill Sorbents, Update IV, EPS 3/SP/3, Environment Canada, 1991
2. Standard Method of Testing Sorbent Performance of Adsorbents, American Society for Testing and Materials, ASTM F 726-81 (1986)

NORTH SLOPE MOBILE TECHNOLOGY
AND
ITS APPLICATION TO SPILL RESPONSE

b y

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ABSTRACT

This paper presents how ARCO Alaska's operation at Prudhoe Bay has applied mobile technology and an innovative concept on the Arctic North Slope for oil spill response. In order to ensure a safe and efficient deployment of resources during a spill response, a rapid deployment equipment delivery system was developed. This multi-functional, modularized system was based on a previously developed chemical delivery system consisting of a primary transport truck equipped with a Dempsey Dumpster Dinosaur skid.

This same modularized concept was used for spill response with the substitution of function specific spill response vans in place of chemical transport tanks. Within this concept, skid mounted mission-specific vans are rapidly deployed to multiple sites in a "fire-brigade" type response. Skid mounted units include land and water containment, recovery, boom deployment, command center, generator skid, restroom facility and skimmer units.

INTRODUCTION

Since the *Exxon Valdez* spill three years ago, North Slope operators have worked aggressively to improve the capabilities of their spill response teams in an effort to be better prepared for a significant spill, should it occur. At ARCO Alaska's Prudhoe Bay operation, improved response preparedness meant setting up new facilities and procuring specialized response equipment. ARCO's equipment procurement philosophy utilizes the concept of a rapid deployment equipment delivery system.

METHODS

Two specially designed, heavy duty, crew cab trucks equipped with a Dempsey Dumpster Dinosaur skid system were built to transport all response vans. These vans were built with skids that are compatible with the system and facilitate quick loading and unloading. Two pup trailers can haul an additional response van behind each truck as shown in Figure 1.



Figure 1 - Heavy Duty Truck with response vans & trailer

The 22-foot modularized response vans contain equipment and supplies for specific spill response functions and can be quickly loaded on trucks and mobilized to multiple sites in a "fire brigade" type response. For initial response, equipment loading time is eliminated, because pre-loaded vans are on trucks and ready to respond. This system is designed to handle the grueling demands of traveling the pipeline haul road. The mission-specific vans will also facilitate marine response because they can

be easily positioned on barge decks for offshore and near shore support activities. ARCO's response van inventory includes:

- Containment Van
- Combination containment/decontamination van
- Self contained recovery unit with rope mop skimmer (Fox Den)
- Boom deployment van
- Oily waste container
- Generator skid
- Envirovac (restroom facilities)
- Field command center
- Utility van

Four vans can be delivered in one trip utilizing both trucks and trailers. All vans are designed to be loaded onto C-130 cargo planes and air-lifted to locations outside the North Slope response area.

The "rubber tracked" Challenger 65, an ATV version of a D6 Caterpillar equipped with a blade and a radio remote winch, is another key component of this rapid delivery system. Even with tongue weight on the Challenger, the load distribution on the 32-inch wide rubber tracks is only 5.2 psi. It has a unique steering system, advanced maneuverability and a travel speed of 22 m.p.h. It is complemented with a "tag-along," rubber-tracked trailer equipped with a Dempsey system. Depicted in Figure 2, this equipment allows deployment of response vans to remote tundra or river delta sites with minimal damage to the environment.

Another key response unit, shown in Figures 3 and 4, is the "Fox Den" skimmer which is a self contained recovery system housing a fox tail rope mop skimmer. Simplicity and a user friendly operation was incorporated into the design of this prototype unit. With safety of operation in mind, a remote control system was designed to allow full wireless remote control of skimmer, engine, crane, and hydraulic systems. The unit is built on a skid and can be quickly deployed to remote sites.



Figure 2 - Challenger 65 with "tag along" trailer & van



Figure 3 - Self contained Fox Den Skimmer Unit w/ rope mop



Figure 4 - Fox Den skimmer with Fox Tail rope mop deployed

Other immediate response equipment include a mobile spill van truck fully equipped with a vikoma vacuum system, and a high pressure steamer to handle smaller spills on roads and pads. An ATV trailer with forward and rear entry is also part of the inventory and used for quick deployment of two snow machines and two four wheel drive ATVs.

The rapid deployment system has proven to be a key asset to ARCO's oil spill response program at Prudhoe Bay. Equipment loading and delivery is a major part of immediate response during an oil spill. This application of mobile technology plays a very important role in helping the spill response team accomplish its immediate response goals by eliminating the "loading time" of necessary response equipment. For the initial response, a large inventory of spill equipment is effective only if it can be rapidly deployed in a safe manner.

ACKNOWLEDGMENTS AND DISCLAIMER

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The techniques presented in this paper are those of the authors and are not necessarily shared by Prudhoe Bay Unit Working Interest Owners.

REMOVAL OF PETROLEUM-DERIVED HYDROCARBONS FROM CONTAMINATED SOILS BY SOLVENT EXTRACTION

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&

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ABSTRACT

The use of solvent extraction for the clean up of oil-contaminated soils has proven to be an effective technology at the bench scale level. Results using a 1,000 g batch system showed extremely high oil removal efficiencies from contaminated sand (up to 98.9%) and peat soil (up to 83.9%). The final oil contaminant concentration for sand varied between 0.06% and 0.39% while that for peat soil varied between 1.52% and 5.21%. The guidelines for the decommissioning and cleanup of sites in Ontario for oil and grease (1 wt.%) were met in all instances for the treated sand. Hexane recovery from diesel contaminated sand and peat soil experiments was approximately 81% and 67% respectively.

INTRODUCTION

The petroleum industry and government agencies are working together to develop technologies for cleaning up oil-contaminated soils. There are many technologies currently available for treating oil-contaminated soil, such as soil vapour extraction, solvent extraction, bioremediation, and incineration. However, many of these technologies are either too expensive to be economically viable or do not clean the soil quickly enough or sufficiently for regulation purposes.

The Emergencies Engineering Division (EED) of Environment Canada initiated a project in September of 1989 involving the removal of petroleum-derived hydrocarbons from contaminated soils by solvent extraction using readily available and relatively inexpensive solvents. This project was jointly funded by EED and the National Groundwater and Soil Remediation Program (GASReP).

BACKGROUND

Solvent extraction is a process whereby a soluble substance is leached from a solid with a liquid solvent. This process has been used effectively in industry for several decades, but it is only recently that it has been applied to the remediation of soils. Most existing soil treatment units employ proprietary solvents resulting in high operating costs. EED chose to evaluate hexane and natural gas condensate (NGC) as solvents because of their low cost and availability at refinery sites, where petroleum hydrocarbon spills are likely to occur. The only drawback to using these solvents is their high flammability which requires an explosion proof facility.

EED has completed laboratory studies employing two solvents (hexane and NGC) for the removal of light crude oil from contaminated soils (sand, peat, and clay). These results suggested that solvent extraction could be an effective technology and efficient process in removing petroleum hydrocarbons from contaminated soils [Hoisak, 1991 and Punt et al., 1991]. Thus further investigation at the bench scale level was recommended prior to designing and building a commercial plant.

The bench scale facility was not complete for testing due to an unexpected delay in obtaining some explosion proof parts and Canadian Standards Association (CSA) approval for the distillation system. This resulted in limited data on the recovery of hexane from the process. Furthermore, NGC could not be evaluated because it had to be pre-distilled to produce a usable solvent.

PROCESS DESCRIPTION

The bench scale process consists of three major steps: solvent washing, settling/decantation/filtration of extract, and solvent recycle. The process uses hexane, a petroleum solvent, which would be available from crude oil processing. The oil-contaminated soil is first contacted with the solvent in a batch multi-stage arrangement within the mixer. The oil/solvent mixture is then decanted from the mixing drum and filtered to prevent solid particles from entering the extract and subsequently hindering the solvent recovery steps. The oil/solvent extract is then distilled for solvent recovery. Whether recovered oil could serve of any use has yet to be determined.

PROCEDURE AND ANALYSIS OF SOILS

Analytical Methods

Initially, freon (1,1,2-Trichlorotrifluoroethane) was used to extract initial and final soil samples in order to determine their percent oil contamination by weight. However, it was discovered, through a few trial runs using dichloromethane (DCM), that this chemical's oil extractive abilities are just as powerful as those of freon. The results using DCM and freon agreed to within 1%. The importance of this discovery is that DCM costs approximately 1/10th the price of freon and therefore DCM was used to extract the remainder of samples in the study.

The percent oil contamination within the sample was calculated as follows:

$$\% \text{ oil contamination} = \frac{\text{weight of oil}}{\text{weight of sample}} \times 100\%$$

The decontamination efficiency was calculated as follows:

$$\text{decontamination efficiency (\%)} = \frac{(\text{initial} - \text{final}) \% \text{ oil}}{\text{initial \% oil}} \times 100\%$$

Preliminary Analysis of Peat and Sand

The average moisture content and fraction of oil present in uncontaminated sand and peat soil are presented in Table 1. The particle size distribution of sand and peat by sieve analysis are presented in Table 2.

Table 1. Average Moisture Content and Fraction of Oil Present in Uncontaminated Soils.

Type of soil	Average Moisture Content (wt. %)	Oil Contamination of Blank Sample (wt. %)
Sand	7.6	0.00
Peat	32.1	0.01

Table 2. Particle Size Distribution of Sand and Peat by Sieve Analysis.

Mesh size	Actual size (micrometers)	Sand (wt. %)	Peat (wt. %)
14	> 1180	28.0	1.8
32	500	27.1	21.9
60	250	21.1	44.0
150	106	21.4	27.9
400	38	2.4	4.4

Soil Contamination and Soil Sample Preparation

Soil samples of between 750 and 1,000 g were used in the bench scale study. The soil samples were added to the mixing chamber along with the desired amount of 24 hour weathered oil. The soil/oil samples were mixed for approximately 10 minutes in a ROSS mixer. This contamination method has two distinct advantages. Firstly, such mixing gives the worst case scenario and therefore the extraction efficiency slightly underscores the project's effectiveness. Secondly, the oil in the soil must be evenly distributed so that a random sample of the contaminated soil will represent the percent contamination of the entire sample.

After mixing the samples, they were allowed to sit for 24 hours prior to their extraction in order that adsorptive and absorptive processes may take place as they would in a real-life oil spill.

Soil Washing

The contaminated sample was added to the mixing container and weighed. The appropriate mass of solvent was added for the first extraction taking into account the desired solvent-to-sample ratio of 2. The slurry was then mixed at the optimum mixing parameters. The mixture was then allowed to settle for 10 minutes prior to decanting through #1 Whatman filter paper. The other extractions were then performed as described above and the extracts were combined.

Centrifugation

The moist extracted solids were then centrifuged in order to remove any more of the oil contaminants and hexane present within the soils. The moist solids were transferred to the centrifuging jars and spun at 4,000 rpm for 15 minutes. Upon completion of the centrifuging process the supernatants atop the centrifuge jars were decanted, filtered through #1 Whatman filter paper and combined with the other extracts from the extraction steps.

Distillation

A simple reflux distillation was employed for separating the oil from the hexane. Once the heating of the hexane extracts began, the temperature of the bottoms increased and then levelled at 69-70°C. The temperature at the top of the reflux condenser stabilized at 68-69°C. The temperature at the top of the reflux column decreased as the solvent fraction in the column diminished. Distillation continued until the temperature at the top of the condenser was between 65.5 and 66.0°C.

Samples of the light ends (tops) and the heavy ends (bottoms) were taken and sent to the chemistry lab for gas chromatography (GC) analysis in order to determine the concentration of hexane in both the distillate and the bottoms. The percent solvent recovery was done on a gravimetric basis and was calculated as follows:

$$\% \text{ hexane recovered} = \frac{\text{weight of hexane recovered}}{\text{total weight of solvent used}} \times 100\%$$

RESULTS

Determination of the Optimum Mixing Parameters for Solvent Extraction

In order to properly assess any engineering process, it is essential that the process be evaluated at optimum experimental parameters. For the solvent extraction process, this means optimizing the mixing time and speed setting along with the number of extractions at the desired solvent-to-sample ratio. A solvent-to-sample ratio of 2 was employed as this was determined to be the optimum based on laboratory results [Hoisak, 1991].

The effect of the number of extractions on the decontamination efficiency of 6% Bunker C-contaminated sand is presented in Table 3. An intermediate contamination of 6% was used since the bench scale study investigated Bunker C-contaminated sand between 2 and 16% and it was known that decontamination efficiency varied with oil contamination.

The decontamination efficiency increases slightly and then levels off with the increase in the number of extractions performed. The optimum number of extractions is 3 as the increased decontamination efficiency observed between 3 and 4 extractions would not justify increased time and labour costs required to perform the additional extraction.

Table 3. The effect of the number of extractions on the decontamination efficiency of 6% Bunker C-contaminated sand samples.

Run No.	No. of Extractions	Oil (wt. %)		Decontamination Efficiency (%)
		Initial	Final	
O-1	1	5.9	0.63	89.3
O-2	2	6.0	0.54	91.0
O-3	3	5.9	0.31	94.7
O-4	4	5.85	0.27	95.4
O-5	5	5.9	0.26	95.6

The next parameters to be optimized were the mixing time and speed. The function of the mixing stage is to provide an adequate combination of agitation and residence time in order to obtain the desired degree of decontamination.

The effect of mixing speed and time on the decontamination efficiency of 2% bunker C-contaminated sands are presented in Tables 4 and 5 respectively. The optimum mixed speed setting and time are 4 (Ross mixer) and 8 minutes respectively as these conditions yield the best decontamination efficiency while minimizing time and power requirements.

Table 4. The Effect of Mixing Speed on the Decontamination Efficiency of 2% Bunker C-contaminated sand. [mixing time: 2 min.]

Run No.	Mixing Speed Setting	Oil (wt. %)		Decontamination Efficiency (%)
		Initial	Final	
O-6	2	1.95	0.24	87.7
O-7	4	1.94	0.19	90.2
O-8	6	1.98	0.19	90.4
O-9	7	1.99	0.19	90.5

Table 5. The effect of mixing time on the decontamination efficiency of 2% Bunker C-contaminated sand. [mixing speed setting: 4]

Run No.	Mixing Time (min)	Oil (wt %)		Decontamination Efficiency (%)
		Initial	Final	
O-10	2	1.94	0.19	90.2
O-11	5	1.97	0.18	90.9
O-12	8	2.08	0.16	92.3
O-13	10	1.95	0.16	91.8

In sum the optimum parameters for Bunker C-contaminated sand are:

Mixing speed: 4 on Ross Mixer
 Mixing time: 8 minutes
 Number of extractions: 3
 Solvent-to-sample ratio: 2

Due to time constraints, these optimum parameters were used for the remainder of bench scale testing regardless of the nature of the soil or the contaminating oil. It should be understood that these parameters may not necessarily represent optimum conditions for all types of soils and oils.

Bunker C-Contaminated Sand and Peat Soil

The results of the hexane extraction of bunker C-contaminated sand and peat soil are presented in Tables 6 and 7 respectively. Decontamination efficiency versus initial oil contaminant concentration in sand and peat soil are plotted in Figures 1 and 2. For the oil concentration range (in sand) investigated, namely from 2.22% to 16.10%, the decontamination efficiency increased from 91.9% to 98.0% while the final oil concentration varied between 0.18% and 0.39%. For the oil concentration range (in peat soil) investigated, namely from 2.5% to 21.0%, the decontamination efficiency increased from 32.0 to 75.2% while the final oil concentration varied from 1.70% to 5.21%.

The extracted soils were quite dark in appearance and were clumped together due to the fact that Bunker C contains a high percentage of heavy ends which cannot be effectively extracted by hexane. [Petti, 1992]

Upon centrifuging the moist solids, the heavy portions of the oil were driven down into the soil. Black pockets of thick viscous hydrocarbons were visible in both the sand and peat soil after centrifuging. It is highly unlikely that Bunker C would be able to penetrate the soils more than a few centimetres in an actual spill due to its high viscosity. Therefore, the extraction efficiency obtained for Bunker C-contaminated soils may substantially underscore the decontamination efficiency since the contacting obtained during sample preparation would not be possible under normal spill conditions. [Petti, 1992]

Table 6. Hexane Extraction of Bunker C-Contaminated Sand at the Optimum Mixing Parameters.

Run No.	Oil (wt. %)		Decontamination Efficiency (%)
	Initial	Final	
S-1	2.22	0.18	91.9
S-2	4.76	0.30	93.7
S-3	6.70	0.33	95.1
S-4	6.90	0.24	96.5
S-5	7.17	0.39	94.6
S-6	9.62	0.33	96.6
S-7	9.80	0.33	96.6
S-8	14.30	0.36	97.5
Sd-8*	14.21	0.35	97.5
S-9	14.74	0.32	97.8
S-10	16.10	0.32	98.0

* Sd = sand sample duplicate

Table 7. Hexane Extraction of Bunker C-contaminated Peat Soil at the Optimum Mixing Parameters.

Run No.	Oil (wt. %)		Decontamination Efficiency (%)
	Initial	Final	
P-1	2.50	1.70	32.0
P-2	5.20	2.90	44.2
P-3	6.98	3.19	54.3
P-4	7.67	3.44	55.1
Pd-4*	7.52	3.33	55.7
P-5	9.30	3.50	62.4
P-6	10.26	3.44	66.5
P-7	13.61	3.91	71.3
P-8	18.82	5.01	73.4
P-9	20.13	5.12	74.6
P-10	21.00	5.21	75.2

* Pd = peat soil sample duplicate

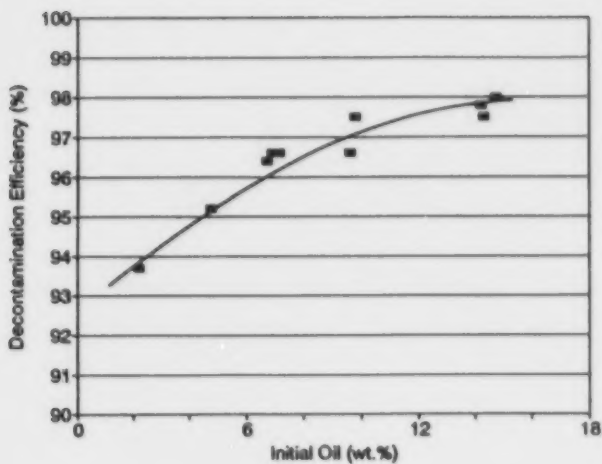


Figure 1. The Effect of Initial Bunker C-Contamination of Sand on Decontamination Efficiency.

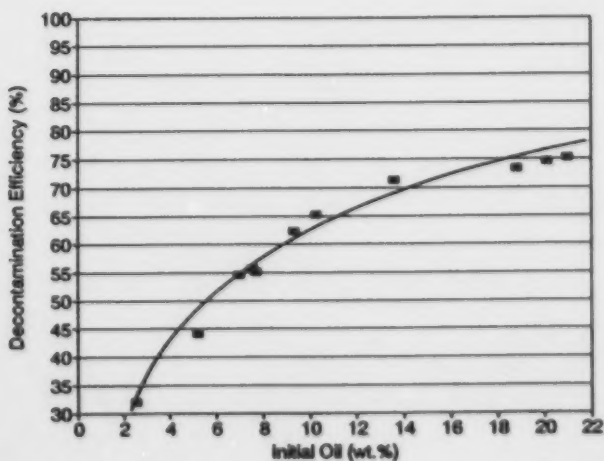


Figure 2. The Effect of Initial Bunker C-Contamination of Peat Soil on Decontamination Efficiency.

Light Crude Oil-Contaminated Sand

The results of the hexane extraction of light crude oil-contaminated sand and peat soil are presented in Tables 8 and 9 respectively. Decontamination efficiency versus initial oil contaminant concentration in sand and peat are plotted in Figures 3 and 4. For the oil concentration range (in sand) investigated, namely from 1.17% to 16.31%, the decontamination efficiency increased from 91.5% to 98.9% while the final oil concentration varied between 0.10% and 0.18%. For the oil concentration range (in peat soil) investigated, namely from 2.57% to 17.23%, the decontamination efficiency increased from 33.9% to 83.9% while the final oil concentration varied between 1.70% and 2.78%.

Light crude oils are complex and variable mixtures of hydrocarbons of different molecular weight and structure and may contain as many as 300 different compounds [Petti, 1992]. It would be unrealistic to assume that hexane would be a suitable solvent for the extraction of all these compounds. When dealing with such a large number of different compounds of different molecular weight and structure, a residual amount of some of the components is expected to remain with the extracted soils.

Table 8. Hexane Extraction of Light Crude Oil-contaminated Sand at the Optimum Mixing Parameters.

Run No.	Oil (wt. %)		Decontamination Efficiency (%)
	Initial	Final	
S-11	1.17	0.10	91.5
S-12	2.43	0.11	95.5
S-13	2.83	0.12	95.8
S-14	5.16	0.16	96.9
S-15	5.87	0.13	97.8
Sd-15*	6.12	0.16	97.4
S-16	7.41	0.17	97.7
S-17	9.41	0.18	98.3
S-18	11.31	0.14	98.8
S-19	12.44	0.15	98.8
S-20	16.31	0.18	98.9

* Sd = sand sample duplicate

Table 9. Hexane Extraction of Light Crude Oil-contaminated Peat Soil at the Optimum Mixing Parameters.

Run No.	Oil (wt. %)		Decontamination Efficiency (%)
	Initial	Final	
P-11	2.57	1.70	33.9
P-12	4.41	2.38	46.0
Pd-12*	4.62	2.41	47.8
P-13	6.50	2.40	63.1
P-14	7.84	2.41	69.3
P-15	9.54	2.43	74.5
P-16	10.28	2.43	76.4
P-17	12.11	2.50	79.4
P-18	13.48	2.51	81.4
P-19	14.12	2.70	80.9
P-20	17.23	2.78	83.9

* Pd = peat soil duplicate

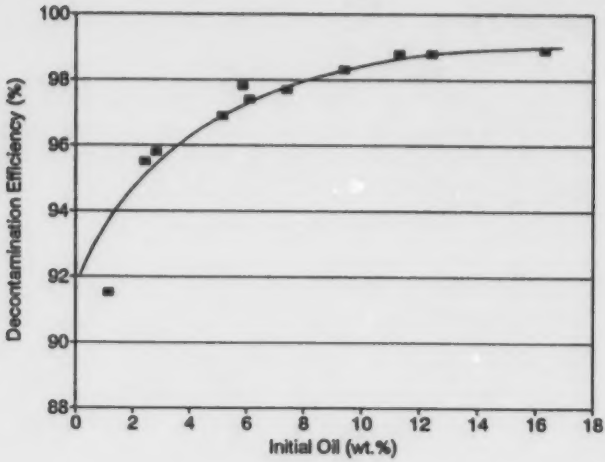


Figure 3. The Effect of Initial Light Crude Oil-Contamination of Sand on Decontamination Efficiency.

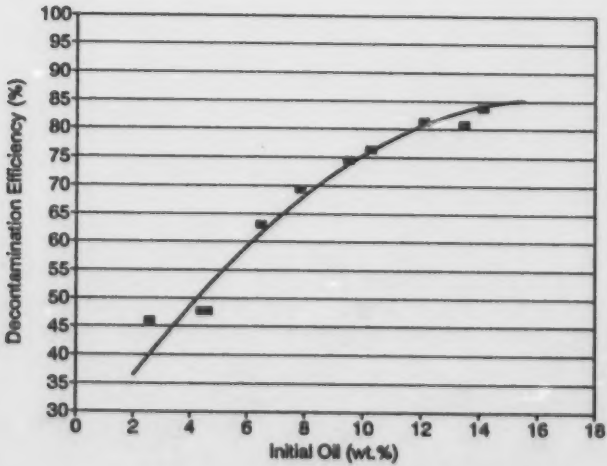


Figure 4. The Effect of Initial Light Crude Oil-Contamination of Peat Soil on Decontamination Efficiency.

Diesel-Contaminated Sand and Peat Soil

The results of the hexane extraction of diesel-contaminated sand and peat soil are presented in Tables 10 and 11. Decontamination efficiency versus initial oil contaminant concentration in sand and peat soil are plotted in Figures 5 and 6. For the oil concentration range (in sand) investigated, namely from 2.42% to 7.83%, the decontamination efficiency remained relatively constant at 97.5% while the final oil concentration varied between 0.06% and 0.19%. For the oil concentration range (in peat soil) investigated, namely from 2.87% to 10.0%, the decontamination efficiency increased from 47.0% to 76.7% while the final oil concentration varied between 1.52% and 2.44%.

Diesel contains a greater amount of light ends as compared to light crude oil. Hexane appears to be a suitable solvent for the extraction of this oil. The extracted soil samples still had a noxious odour even though the residual oil was as low as 0.06% in some extracted sand samples. [Petti, 1992]

The recycling of hexane reduces the cost of the soil treatment and the volume of waste. As previously mentioned, unforeseen delays in obtaining an explosion proof hot plate resulted in obtaining only solvent recovery data for diesel-contaminated soils. Hexane recovery for sand and peat is approximately 81% and 67% respectively regardless of the degree of initial diesel-contamination.

The average percent hexane in the condensate was approximately 99.8%, while a blank run of pure hexane gave a purity of 99.9%. Thus one can conclude that the distilled extract produces a recycled solvent which is suitable for reuse.

Table 9. Hexane Extraction of Diesel-Contaminated Sand at the Optimum Mixing Parameters.

Run No.	Oil (wt. %)		Decontamination Efficiency (%)	Solvent Recovery (%)
	Initial	Final		
S-21	7.83	0.19	97.6	79.8
S-22	6.42	0.17	97.4	81.3
S-23	4.99	0.13	97.4	79.4
S-24	4.50	0.11	97.6	81.7
S-25	2.42	0.06	97.5	82.0

Table 10. Hexane Extraction of Diesel-Contaminated Peat Soil at the Optimum Mixing Parameters.

Run No.	Oil (wt. %)		Decontamination Efficiency (%)	Solvent Recovery (%)
	Initial	Final		
P-21	10.0	2.44	75.6	66.4
P-22	9.51	2.22	76.7	65.9
P-23	7.16	2.23	68.9	66.8
P-24	5.30	2.00	62.3	67.2
P-25	2.87	1.52	47.0	67.3

COMPARISON TO SOIL REMEDIATION GUIDELINES AND LABORATORY SCALE RESULTS

The guidelines for the decommissioning and cleanup of sites in Ontario for oil and grease set out by the Waste Management Branch of the Ontario Ministry of the Environment (MOE) in February 1989 is 10,000 ppm (1 wt. %). These guidelines were met in all instances for sand contaminated with light crude oil, diesel or Bunker C as the final oil contaminant concentration varied between 0.06% and 0.39%. The final oil contaminant concentration for peat soil varied between 1.52% and 5.21% and thus did not comply with the MOE guidelines. It should be emphasized that these are only guidelines and not regulations.

In general, the decontamination efficiencies at the bench scale are slightly lower but consistent with those at the laboratory scale. Once again, decontamination efficiencies with sand are greater than those with peat and the final oil concentration in sand is less than that in peat.

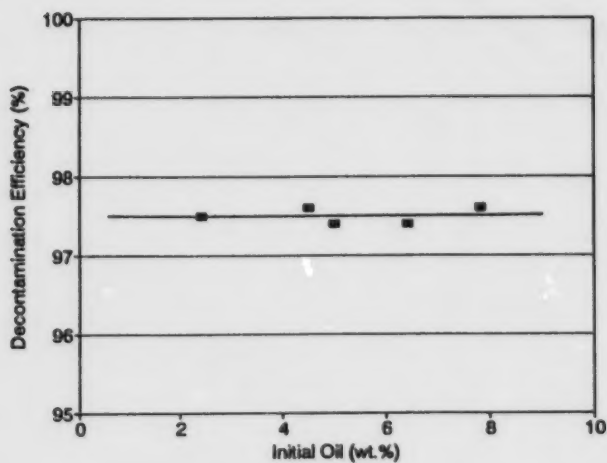


Figure 5. The Effect of Initial Diesel-Contamination of Sand on Decontamination Efficiency.

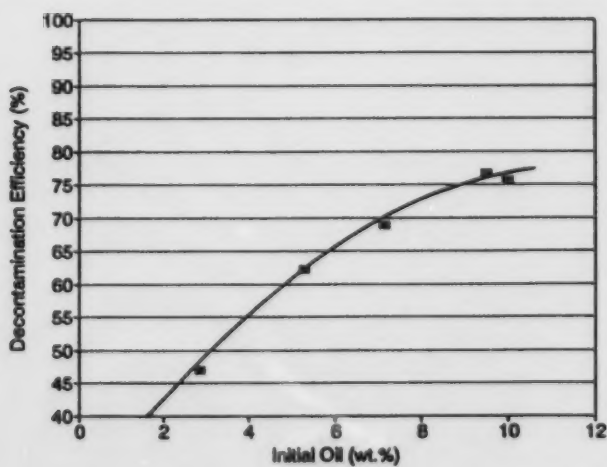


Figure 6. The Effect of Initial Diesel Contamination of Peat Soil on Decontamination Efficiency.

CONCLUSIONS AND RECOMMENDATIONS

Results using a 1,000 g batch system showed extremely high oil removal efficiencies from contaminated sand (up to 98.9%) and peat soil (up to 83.9%). The final oil contaminant concentration for sand varied between 0.06% and 0.39% while that for peat soil varied between 1.52% and 5.21%. The guidelines for the decommissioning and cleanup of sites in Ontario for oil and grease (1 wt. %) were met in all instances for the treated sand but not for the peat soil. Hexane recovery from diesel contaminated sand and peat soil experiments was approximately 81% and 67% respectively.

The solvent extraction process seems to be a promising technology for the treatment of contaminated soils. However, its potential will depend on the environmental regulations and the allowable limits of oil and grease for returning treated soil to its original place. The treated soil may need to be subsequently treated to destroy the residual contaminants or be recycled through the process to meet the environmental regulations at the municipal, provincial, or federal level. Furthermore, as regulations become more stringent, other constituents, such as benzene, toluene, etc. will have to be analyzed.

This treatability study has proven to be very effective for soils that have been in contact with petroleum hydrocarbons for short periods of time. However, this process must be evaluated for soils which have been in contact with petroleum hydrocarbons for longer periods of time resulting in only the heavy, viscous components remaining.

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VISCOSITY AND DRAG REDUCTION FOR TEMPORARY STORAGE AND TRANSFER OF WEATHERED CRUDE OILS AND EMULSIONS

by

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INTRODUCTION

This study was undertaken as a search for and preliminary, engineering assessment of various concepts for the reduction in viscosity of weathered crude oils and emulsions recovered during spill cleanup operations and the reduction in skin friction drag associated with pumping the recovered fluids. The objective was to identify concepts and systems which, alone or in combination with others, could significantly reduce pumping problems associated with the recovery at sea of Grand Bank's crude oils and their emulsions. All potentially useful concepts had to fit into a modular, road-transportable, temporary storage and transfer system for vessels-of-opportunity.

LITERATURE SEARCH

Two literature searches were conducted by the Canadian Institute for Scientific and Technical Information; one on the subject of drag reduction and the other on the subject of flow improvement. Six databases were searched, namely:

Database	Dates Searched
APILIT	(1964-1991.05)
CHEMICAL ABSTRACTS CA FILE	(1967-1991.07)
ENGINEERING INDEX	(1970-1991.06)
ENGINEERING INDEX MEETINGS	(1982.07-1991)
FLUIDEX	(1973-1990.12)
FOOD SCIENCE & TECHNOLOGY	(1969-1991.06)

In total 735 "hits" were obtained using the search strategy developed by CISTI; of these, 67 seemed applicable and were ordered and reviewed. In addition, searches of the Emergency Sciences Division (ESD) library of Environment Canada, Conservation and Protection and the S.L. Ross library produced 4 documents and 24 documents respectively; Mr. Greg Warbanski of ESRI provided 2 documents. A description of the various databases searched and the search strategy may be found in the report (S.L. Ross and Glosten 1992).

PRELIMINARY EVALUATION OF CONCEPTS

Each of the concepts identified in the literature search was subjected to an assessment of its suitability for further evaluation. The specific questions asked about each concept were:

1. Is there sufficient data to make a reasonable assessment of the method?
2. What reduction in viscosity can reasonably be expected from the method assuming initial viscosities ranging from 20,000 cp to 200,000 cp.?
3. What reduction in drag forces can reasonably be expected from the method selected, assuming initial viscosity ranging from 20,000 cp to 200,000 cp.?
4. Does the method have potential for insuring the continuous flow of high viscosity oils/emulsions into the intakes of pumps used to evacuate storage tanks?
5. Does this method offer greater potential if combined with another?

ASSESSMENT RESULTS

Table 1 shows the matrix of results for the preliminary evaluation of the drag reduction and flow improvement concepts uncovered by the literature search. The assessment of each is detailed as follows:

Chemical Additives

Drag Reducing Agents

Drag reducing agents (DRA's) are long-chain polymers that reduce skin friction in pipes in turbulent flow (DRA's are ineffective in laminar flow). They have been used to increase flow or reduce required pump pressures in:

- oil well fracing;
- firefighting;
- irrigation;
- sewers;
- floodwater disposal;
- slurry pipeline transport;
- crude oil pipelines;
- heating systems;
- jet cutting;
- biomedical; and
- marine hull applications

Of particular interest is their use in pipelining of crudes (their first commercial application was in increasing the flow in the Trans-Alaska Pipeline by 10-20% using 35-50 ppm DRA) where they have been extensively used for the transport of "viscous" crude oils. Drag reductions of 10-70% have been achieved in these applications. Their use for improved pumping of emulsions is reported in one paper.

Sellin et al, 1983, report that drag reducing agents have the following benefits when applied to turbulent flow situations:

- * for positive displacement pumps a reduction in pressure gradient is achieved.
- * for constant head applications an increase in discharge rate is achieved.

Concept	Sufficient Data?	Expected Viscosity Reduction	TABLE 1 Drag Power Reduction	Continuous Flow in Solution	Greater Potential if Combined	Recommended for Further Analysis
Chemical Additives Drag Reducing Agents	yes	0	10-70% in turbulent flow	no	don't know	yes
Pour Point Depressants	yes	high at temp $\geq$ PP	high mol's in yield stress	yes	yes, heating and emulsion breakers	yes
Viscosity Reducing Agents	yes	20-50%	none	probably	yes best	no
Emulsion Breaking Emulsion Breakers	yes	10-100 times	don't know	yes	best, mixing	yes
Solvent Siphon	maybe	20-60% with Terra Nova crude	none	yes, if used upstream of tank	yes, with emulsion breakers	no
Increase Diameter of Pipes/Tanks	no	none	10 times	no	yes, with any other	no
Free Water Injection	yes	93-98%	none	yes		no
Pipe Coatings	yes	0	<10%	no	no	yes (Teflon coatings for cleaning)
Annular Water Injectors	yes	0	reduce pressure drop by 10-15 times	no	don't know	yes
Heating	yes	20°C = 50%	0	yes	yes, chemical methods	no, except indirect heating of top layer
Shearing	yes	depends on oil and T	0	yes	yes	yes
Pressurization	yes	0	0	no	no	no
Heavy Oil Industry Methods	yes	none on heating & viscosity reducing agents	0	yes	yes	no

- * for centrifugal or other variable rate/head pumps the relationship between rate and head improves (i.e. reduced pressure and increased flow).

Small, 1983, gives the following rules for selection appropriate drag reducing agents (DRA's):

- * the DRA must be soluble in the fluid
- * the DRA must not break down in the existing flow turbulence
- * the DRA must not adversely affect downstream operations (i.e. refining etc.)

Lester, 1985, notes that pumps degrade the performance of DRA's by shearing and breaking the long molecules. As such, they must be injected at the discharge side of pumps.

Hale, 1984, gives the following equations for assessing the field effectiveness of DRA use:

$$\% \text{ D.R.} = (\Delta P - \Delta P) / \Delta P \times 100$$

where % D.R. = percent drag reduction

ΔP = system pressure drag prior to DRA addition [kPA]

ΔP = system pressure drag after DRA addition [kPA]

and:

$$\% \text{ throughput increase} = ((1/(1-(\%DR/100)))^{0.55}-1) \times 100$$

The use of DRA's for improved pumping of recovered waxy oil and emulsions was considered worthy of further assessment because: they are proven entities; work at low concentrations; and, would not likely require extensive, heavy and large equipment.

Pour Point Depressants

Pour point depressants are chemicals which interfere with the crystallization of waxes on cooling which cause oils to "gel". These chemicals are very "oil-specific" but very effective with their candidate oil. They are widely used for the pipelining of waxy Indian and African crudes and in fuels for very cold climates (i.e. P-50 diesel). Additions of 100 ppm of pour point depressants can reduce pour points by 10-30°C and reduce yield stresses by 60-100%. Pour point depressants can also reduce viscosities of fluids at temperatures above their pour points.

When a waxy oil is cooled below its cloud point (the temperature at which wax crystals begin to appear in the liquid) the wax gradually crystallizes and separates from solution. The thin plate- or needle-like crystals agglomerate and form a loose gel structure resulting in non-Newtonian flow characteristics.

The addition of pour point depressants prevent or slow down this agglomeration by changing the size, orientation and interaction of the crystals and thus reduces the temperature at which a gel structure is formed. In order for pour point depressants to be effective, they must be added at a temperature warmer than the cloud point of the oil.

It is worthy of note that some crude oils are unaffected by any pour point depressant (Schuster and Magill 1989); that reheating of a treated sample may destroy the effect of the

additive (Irani and Zajac 1982); and, that pour point depressants have resulted in flow improvements in oil-field emulsions of 42% water by volume (Irani and Zajac 1982).

The use of pour point depressants is considered worthy of further assessment because, despite their "oil-specific" nature, they offer the potential to greatly improve both flow properties and the ability of otherwise gelled oil in tanks to flow towards pump suction. It is likely that testing will be required to choose the best suited chemical(s).

Viscosity Reduction Agents

One paper discusses the reduction in viscosity of a heavy crude by using dissolved methane and propane for Enhanced Oil Recovery (EOR). The second paper discusses the reduction in viscosity of viscous oils by the addition of small amounts of methanol. Addition of 3-6% methanol by volume resulted in a 20-50% reduction in oil viscosity. Contacts with the heavy oil production industry in Canada indicate that a diluent (naphtha or light ends) is mixed with the bitumen in order to reduce its viscosity below pumpability limits.

Since relatively large amounts of volatile fluids or gases would be required onboard a vessel to utilize this technique, the use of viscosity reduction agents is not recommended for further study.

Emulsion Breaking

Steam Siphon

Several studies examining the use of a steam siphon as an emulsion breaking device have been conducted. Results have indicated that this method is effective. The combination of breaking the water-in-oil emulsions and raising the temperature of the oil/emulsion results in significant viscosity reductions (20 to 60%) and therefore increased pumpability.

While this method has potential in the area of transporting and handling of viscous oil/emulsions, its power and fresh water requirements make it unsuitable for offshore use; a 10 tonne/hr (60-70 bbl/hr) unit could only process 20% of the operational output of a GT-260 skimmer. A 10 tonne/hr steam siphon would require a 980 kW steam boiler and consume 1 tonne per hour of fresh water.

Emulsion Breakers

Emulsion breakers are surfactants that destabilize an oil/water interface in an emulsion, and permit water droplet coalescence. The chemicals tend to be "oil-specific" and require mixing to be effective. Many commercial brands are available and have been tested. Doses of 250-1000 ppm can cause complete emulsion breakage in 1-2 hours (50% in 10-20 minutes or less) and reductions in viscosity by factors in the hundreds. Their use is designed into the latest offshore skimmers produced in Norway and many existing skimmers are being retrofitted with emulsion breaking chemical injection capability.

The use of emulsification breakers in oil spill recovery operations is the subject of a recent CPA-sponsored study. The following is an excerpt from that report (S.L. Ross et al 1992).

Various techniques for chemical demulsification are described by Van Oudenhoven et al. (1980). Separation times of 10 to 20 minutes are cited but separation time is expected to increase as the stability of the emulsion increases.

Documentation of actual use of emulsion breakers during oil spill clean up operations is limited and the results are mixed. During the cleanup of the Amoco Cadiz spill, emulsion breakers were used in the intermediate storage tanks and then in the onshore mobile vacuum tanks. It was noted that the major benefit of using emulsion breakers was an immediate reduction in viscosity which sped up transfer operations and facilitated the separation of debris from mousse. Some effectiveness in removing water from emulsions was found, provided that sufficient mixing was applied. It was suggested that the mixing energy provided during these transfer operations was insufficient to effectively distribute the demulsifier and promote separation of the emulsion. To make more effective use of emulsion breakers, it was recommended that demulsifiers be injected in-line upstream of the pump at a proper metered dose.

It was found that 2 to 3 weeks after the spill, the demulsifiers were ineffective on weathered Amoco Cadiz mousse at ordinary temperatures, and that heat had to be applied for pumping (Bocard et al., 1979; Bocard and Gatellier, 1981). Similar results were found when demulsifiers were tested on mousse generated from a long-term experimental spill. It was hypothesized that products of photo-oxidation greatly enhance emulsion stability. Other studies offer data in support of this hypothesis. Recently, Brandvik and Daling (1990) found that photolyzed oils have a greater tendency to form stable emulsions and that these emulsions were more resistant to chemical demulsification. This resistance to demulsifiers can not be attributed to an increase in viscosity but is likely a result of the photo-oxidized compounds enhancing the stability and structure of the interfacial film. Thus, emulsifier molecules are effectively prevented from entering the interface and disturbing the interfacial film.

Further evaluation of emulsion breaking chemicals is strongly recommended because of their proven ability to quickly break emulsions at low dosage rates and with minimal additional equipment. It is likely that testing will be required to select the optimum chemical(s) for Grand Bank's oils.

Diameter of Pipes/Hoses

The use of large diameter pipes or hoses has been considered as a means of reducing friction losses in transfer operations.

It can be shown that, for Newtonian fluids in laminar flow, skin friction losses are proportional to the inverse fourth power of the hose diameter (doubling the hose diameter reduces the head loss by a factor of 16). For thixotropic, pseudoplastic fluids, like waxy crude oils at temperatures near their pour point, the dependence of skin friction on hose diameter will be less dramatic and perhaps even reversed (high mixing rates in turbulent flow - i.e. smaller diameter hoses - could reduce viscosities by several orders of magnitude and thus greatly reduce friction losses); insufficient rheological data exists to quantify this relationship for waxy oils and emulsions.

As well, other factors come into play when selecting pipe and hose diameters, such as economics, pump sizes, etc. Many techniques exist for the selection of economic pipe diameters for plants and refineries. One nomograph for Schedule 40 steel pipe at a flow rate of 6.4 m³/min (transferring the product of 8 hours skimming at 300 bbl/hr in 1 hour) with

a viscosity of 100,000 cp yields an economic pipe diameter of 8 inches. From the perspective of common oil spill pump discharge sizes and hose handleability a hose size of 6" is recommended. This is the transfer hose size chosen by Framo, NOFO and most offshore skimmer manufacturers for their oil recovery and transfer systems.

Free Water Injection

The creation of a water slurry to transport solids or viscous fluids in suspension in pipelines is common practise. Two papers related to this drag reduction technique were uncovered during the literature search. The principle behind this flow improvement technique is to add enough water to create a slurry of dispersed oil in water. This would entail dilution of the oil stream with many times its flowrate of water. Because of the desire to reduce free water in oil spill recovery operations; the potential emulsification problem; and, the need for downstream separators, this method was not considered applicable for this study.

In addition two related studies were uncovered, as summarized below.

Oil-in-Water Emulsion Study

One paper was reviewed on the use of surfactant-producing bacteria in the reduction of crude oil viscosity. The growth of a specific strain of oil bacteria on heavy crude oil resulted in a 93-98% reduction in oil viscosity by formation of stable oil-in-water emulsions with extra-cellular glycolipid. However, no indication was given as to the time required for a significant reduction in viscosity to be observed.

This method probably has little potential relevance and application to technologies involving the processing or transporting of heavy crude oil or emulsions over short (i.e. less than several days) time periods. No further assessment was recommended.

Drag Reduction by Air Injection

One paper was reviewed, with reference to several other studies, indicating that drag reduction may occur as a result of air injection in plug or slug flow regimes with shear-thinning liquids and pseudo-homogeneous slurries. Reductions in axial pressure gradient of up to 85% were obtained with a suspension of anthracite in water. No drag reduction can take place if the suspension is initially in turbulent flow prior to air injection.

This technique depends on interspersing the liquid fraction being pumped with bubbles or slugs of air. Although interesting and potentially useful in terms of air-lift pumping, insufficient data on this method prevented a full assessment of its applicability to the handling of highly viscous oils and emulsions.

Pipe Coatings

No specific papers relating to pipe coatings as a technique for reducing drag were uncovered by the literature search. In general, pipe coatings are used to improve a pipe's resistance to attack by the fluid carried. In laminar flow, pipe coatings have no effect on friction losses; in turbulent flow their effect is related to decreases in the ratio of internal pipe roughness to pipe diameter. No data could be readily obtained on the surface roughness of flexible hose; however, as an illustration, the Reynolds number would have to exceed

100,000 for there to be an appreciable difference in the friction loss of standard steel pipe and glass-lined steel pipe. Teflon and its related coatings are recommended as pipe coatings for sticky, viscous fluid service. Their use in tanks, valves, etc. may be justified from an "ease of cleaning" perspective; their use in plastic/rubber hose may also be justified from a cleaning perspective.

Annular Water Injectors

This technique of drag reduction involves the creation of a stable annulus of water flowing in a pipe with a core of viscous oil. The technique seems ideally suited for oil spill applications since it is simple, can use seawater, requires only 6-8% water by volume and results in great reductions in pressure drop (by about a factor of 5-10). The fluid velocities in the hose must be at least 0.5 m/s and the relative velocity between the two fluids should be less than 0.5 m/s. The technique has been tested with 4" and 6" hoses and 8" pipelines.

The Venezuelan national oil company, Petroles de Venezuela SA, is using annular water injection to transport very viscous crudes in pipelines (Tippee 1988). These crudes range in API gravity from 8° to 14° (the API gravity of fresh water is 10°) and in viscosity from 3000 to greater than 100,000 cp. With 8% of the total flowrate made up of water in an annulus and the remaining 92% a 60,000 cp crude with an API gravity of 9° moving at 0.5 m/s in an 8" pipeline test loop the pressure drop was 17 to 20 kPa. Without the water annulus the pressure drop was 3.8×10^5 kPa, some 18,000 times higher. They report screw pumps as being the most effective oil movers for this application.

Peigne and Cessou (1989) report on the testing of an annual water injector for improved pumping of viscous oils. This study involved 3 phases: a literature review, laboratory tests and field trials.

The small-scale tests showed that:

- The lowest percentage of water that results in a maximum reduction of pressure drop is about 7 percent (in relation to the total volume).
- For speeds of viscous liquids greater than 0.2 m/s, a water film was always produced.
- The presence of bends, diaphragms or roughness along the tubes did not destroy the water film.
- The ratio of the speed of water to the speed of the viscous liquid at the injector outlet must always be greater than or equal to 1 in order to obtain good results.
- The type of water injected does not seem to have an influence on the flow phenomena; sea water can be used. The type of oil to be transferred does not seem to influence the results.
- Annular water injection cut the pressure drop by a factor of at least 25 for the diameter of the pipe tested.

Large-scale tests involving Bunker C and both screw-type (EGMO W double screw) and centrifugal (Framo TK5) oil pumps resulted in the following conclusions:

- a small flowrate of water (6 percent of the oil flow) reduced pressure drop by factors of 10 to 20.
- it was not necessary to begin with the hoses filled with water to establish a stable annular flow.
- no specialized water flow control system was required, as long as the flow exceeded the 6% minimum.

For the reasons delineated above, further assessment of annular water injectors was undertaken.

A related drag reduction technique was recently tested by the Oil Spill Service Centre in Southampton, U.K. This concept involved the injection of hot or cold high-pressure water (10,000 kPa = 1500 psig) into the discharge side of a pump. An "off-the-shelf" high pressure washer was used to inject 23 L/min (5 gal/min) of water. This visibly increased flow and reduced the pump load by 10%. The concept was described as "similar to the CEDRE annular water injection concept" (David Salt, pers comm).

Heating

Bulk heating of viscous fluids is the standard method of viscosity and drag reduction in the heavy oil industry, shipping residual fuel oils and refining. A "rule of thumb" is that an increase of 20°C halves an oil's viscosity. A possible alternative to bulk heating is infrared heating using electric or gas-fired radiant heaters.

Heating of the recovered oil will be a necessary part of any waxy/viscous oil storage and recovery system; however, the energy requirements to heat the entire recovered fluid stream would be high. Assessment of techniques to selectively heat only the oil-portion of the recovered fluids was considered worthwhile.

To this end the use of two heat-transfer techniques was assessed: infrared heaters and hot-oil panel coils. Infrared heaters, through attractive from an energy use perspective (they would heat only the top layer of a fluid in a tank - the likely location of pure oil in the tank), suffer from a safety problem: they are not designed for use in potentially flammable or explosive atmospheres. The option of infrared heaters was however recommended for further assessment to see if this problem could be solved.

Hot-oil heat transfer processes are well known and widely used in the marine industry. Portable, diesel-fired heaters can be used to heat special oils for pumping through panel coils that can be inserted into tanks at specified locations for selective heating. One distinct advantage of this approach is that it can utilize diesel fuel as the energy source, a commodity usually in good supply on an oilfield supply vessel. This negates the requirements for large electric generators to accompany the system.

The use of portable hot-oil heaters and panel coils placed selectively in tanks was recommended for further assessment.

Shearing the Oil

Shearing, or mixing, a waxy oil at temperatures near its pour point, significantly reduces its viscosity and prevents the development of a yield stress (or gelling). Many types

of mixers are commonly available for tanks, however they are heavy, cumbersome and would impede tank cleaning. One simple alternative is to use air pumped into the bottom of the tank to gently mix the contents. This is used in the pulp and paper industry to maintain viscous pulp in suspension. The concept is simple, requires no moving parts and could possibly operate with ship's air.

The use of air sparged through pipes at the bottom of fluid storage tanks is well-known. It has been used since the early 1900's in the pulp and petroleum industries. The technique does not require large, complex machinery installed in the tank and can provide low-to-medium levels of mixing. One advantage to this technique is that the prime mover (an air compressor) can be readily rented at the time of the spill; one potential disadvantage is the generation of a potential flammable airstream from the mixed tank(s) that will have to be ducted to a safe discharge location.

Another potentially applicable technology is to use comminutors, grinders and in-line shredders common to the sewage treatment and food industries to both reduce/grind entrained debris in the recovered oil and provide initial mixing to the fluid prior to its entering a pump suction.

The use of grinders/comminutors has been reported (Nadeau 1977) in US Navy harbour skimmers. When combined with viscous oil/debris handling pumps they provide an excellent method for processing (as opposed to separating) debris in the recovered fluid stream. Although the presence of debris in recovered fluids on the Grand Banks is less likely than near shore, it is still quite possible that the skimmer output could contain carcasses, rope ends, plastic, lumber, etc.

Both ideas (air agitation and pump suction grinders) were recommended for further study.

SUMMARY

Of the concepts assessed, seven were recommended for further study. The seven that were recommended, and the reasons, are:

- drag reducing agents - a low dosage of these polymers can achieve medium reductions in drag and consequent increases in flow rate; need to determine likely flow regimes and potential effectiveness with high viscosity oils, emulsions and in the presence of free water;
- pour point depressants have the potential to greatly improve pumpability and flowability of oil in storage tanks; need to assess efficacy with emulsions, in the presence of free water and effects of use with emulsion breakers;
- emulsion breakers show great potential for improving flowability and reducing required storage volumes;
- annular water injection shows great promise for the pumping of very viscous product through long hoses with little pressure drop.
- the efficacy of Teflon coatings for ease of cleaning for tanks and valves
- the use of air injection for mixing viscous fluid in a tank to ensure flow to pump suction; need to assess safety aspects
- the use of grinders at tank inlets and pump suction

CONCEPTUAL SYSTEM DESIGN AND FURTHER ASSESSMENT OF PROMISING CONCEPTS

Each of the most promising concepts identified above was subjected to a detailed review. In order to give this further assessment a solid basis an oil recovery system was hypothesized. This involved the use of a Pharos Marine GT-260 skimmer deployed from the aft deck of an oilfield supply vessel. Booming operations were presumed to be the role of other vessels.

BASIS

The detailed assessment of the various systems and initial scoping of vessel deck layouts, etc. was based on a vessel-of-opportunity (an oilfield supply vessel) approach with the vessel dedicated to oil recovery operations (i.e., another ship looks after transport and deployment of the booms). Road transportability and modular construction of selected temporary storage and transfer equipment were also key criteria.

Equipment Capacity Requirements:

The following gives the ranges of values for volumes and/or flowrates for the suite of equipment required to implement all the viscosity/drag reduction concepts recommended for a vessel-of-opportunity oil spill recovery, temporary storage and transfer system for waxy oils and their emulsions.

Skimmer

* Pharos Marine GT-260 deployed by a Framo ACW-400 crane

- weights: crane -7045 kg
 - skimmer - 545 kg
 - power pack - 1850 kg dry + 100 L diesel fuel + 300 L hydraulic
 - hose reel -1091 kg
 - GT-260 cab - 1130 kg
- footprints:
 - crane - 2.5 m x 9.2 m
 - skimmer - 3.6 m x 2.9 m
 - cab - 1.6 m x 2.3 m
 - power pack - 1.9 m x 1.2 m
 - hosereel - 2.1 m x 1.5 m
- capacity:

based on tank and offshore tests of the Pharos Marine GT-185 skimmer (a smaller version of the GT-260) the following operational recovery rates (Buist and Potter 1988, Buist and Potter, 1989) have been calculated (scaling based on ratio of "nameplate" recovery rates of GT-260 and GT-185 = 100 m³/hr / 45 m³/hr) to be:

for $\mu = 20,000$ cP; oil recovery rate = 45m³/hr + free water recovery rate = 22 m³/hr for a total of 67 m³/hr

for $\mu = 200,000$ cP; oil recovery rate = 25 m³/hr + free water recovery rate = 42 m³/hr for a total of 67 m³/hr

Eastcoast Spill Response Inc. (ESRI) has measured the water pumping rate of a GT-260 at 62 m³/hr through 40 m of 6" hose against a 5 m static head.

Emulsion Breaker System

- * injected directly into hopper of skimmer
 - * uses Alcopol at approximately 250 ppm
 - * Alcopol use rate is therefore approximately 17 L/hr, or 134 to 268 L/day (based on 8 to 16 hr days; see below) = $\frac{1}{4}$ to 1 drum per day:
 - * 20-day supply (assumed) is 20 drums of Alcopol weighing approximately 4500 kg and four N₂ cylinders
 - * uses pressurized tank/metering valve supply system
 - * footprint = 1.9 m x 1.6 m
 - * weight = 725 kg
- (consists of 2 drums Alcopol, metering tank, four N₂ cylinders, 40 + 20 m hydraulic hose and 7 m of air hose)

Pour Point Depressants

- * would be injected into storage tank inlet
- * nominal concentration of 100 ppm translates to 50 to 100 L/day chemical usage rate (20-day supply on board assumed required = 1 to 2 m³)
- * could involve use of an in-line, static mixer or grinder/comminuter at storage tank inlet to promote mixing of chemical(s)
- * same type of injection system as for emulsion breaker is assumed

Storage Tank

- * storage volume required based on recovery rates x available skimming time in one day on Grand Banks
- * hours of daylight on Grand Banks = 8 to 16
- * if free and demulsified water are decanted the minimum storage volume required is: 22 m³/hr x 8 to 16 hr x (1 - 0.75) = 44 to 88 m³ for recovery of a 200,000 cSt emulsion with 75 % water; or, 45 m³/hr x 8 to 16 hr = 360 to 720 m³ for recovery of a 20,000 cSt unemulsified oil
- * if free and emulsified water are not decanted the storage volumes required are: (25 + 42) m³/hr x 8 to 16 hr = 540 to 1070 m³

Air Sparging to Prevent Gelling

- * based on Lamont 1958, the volume of free air required for moderate mixing of a tank 3 m deep is 2.1 m³/min m² of liquid surface area
- * for the range of storage tank sizes above the free air requirement ranges from approximately 31 to 750 m³/min; high pressure air is not required

IR Heating

- * based on preliminary information from Brant Radiant Heaters the following could possibly be used in the top of the storage tank to heat up only the oil or emulsion by 20 °C ($C_p = 464 \text{ watt-hrs/m}^3 \text{ } ^\circ\text{C}$):
 - for a 44 or 88 m³ storage tank 60 kW of A.C. power (240 V single phase to 575 V 3-phase) is required for 4 x 15 kW "Electro-Ray" units
 - for a 540 or 1070 m³ storage tank 240 kW of A.C. power is required for 16 x 15 kW "Electro-Ray" units

Transfer Pump

- * design flowrate based on transferring contents of one day's recovery to nearby tanker or barge in one to two hours
- * range of flowrates is:
 - for the 44m³ storage tank emptied in two hours - 22 m³/hr
 - for the 1070 m³ storage tank emptied in one hour - 1070 m³/hr
- * range of viscosities is 20,000 to 200,000 cP
- * operating temperature range is -15 to 40 °C
- * design heads:
 - suction - 0.0 m
 - discharge - 61 m of 6" diameter flexible hose + 10 m rise + valve, reducer, ell, etc. losses
- * must be able to process some solids (i.e. organics, sorbents, rope ends, etc.)

Inlet Grinder/Comminuter

- * must have liquid throughput equal to that of selected pump
- * must be able to grind/macerate solids noted above to a size that can be processed by the selected pump
- * should impart mixing to fluid surrounding pump inlet to overcome yield stress in gelled oil
- * ideally forms integral part of selected pump
- * if not integral, it should fit easily on to pump inlet and not be excessively bulky
- * should be powered by pump power supply, but independently controlled

Drag Reducing Agents (DRA)

- * injected downstream of transfer pump (internal pump turbulence will destroy DRA's effectiveness)
- * based on 35 ppm nominal dose the required flowrate of DRA is:
 - for the 44m³ storage tank emptied in two hours (22 m³/hr) - 0.8 L/hr
 - for the 1070 m³ storage tank emptied in one hour (1070 m³/hr) - 37 L/hr
- * the 20-day operational storage requirement would be 32 to 740 L
- * same type of injection system as for emulsion breaker is assumed

Annular Water Injection

- * injected downstream of transfer pump using special annular injector
- * requires seawater at a flowrate of 6 to 8% of transfer pump rate
- * nominal injection rates thus are 1.3 to 85.6 m³/hr

Transfer Hose

- * 61 m x 6" floating hose
- * need capability to purge line with seawater

Individual Concept Analysis

Emulsion Breaker System

This system already exists. ESRI has designed and constructed an inert gas powered injection system utilizing the emulsion-breaker ALCOPOL. The efficacy of emulsion breakers is the subject of a recent CPA study (S.L. Ross et al 1992), thus the subject will not be reviewed in more detail here.

Pour Point Depressants

The injection of pour point depressants must be done at a temperature above the pour point of the oil (depressants affect the manner in which the waxes precipitate from solution on cooling and will not affect already gelled oil) but are reportedly effective on emulsions. It is clear that pour point depressants can be effective but must be injected after heating of the product and in the presence of additional mixing energy.

The effectiveness of these chemicals is highly oil-specific and testing would be required to select the most effective product or mixture on specific crude oils. Regardless, because of their advantages in yield stress and viscosity reduction, their use is recommended.

Solids Handling

A shredder device such as a Franklin Miller Super Shredder is capable of reducing a variety of materials, such as rope, wood, light metal and organic solids should be installed immediately at the outlet of the skimmer hose. A bypass should be fitted, as under some conditions the action of the shredder could promote further formation of a stable emulsion of the free water in the reclaimed product. Hopefully, the addition of emulsion breaker at the skimmer will alleviate this tendency. A second shredder might also be fitted on the transfer pump suction manifold.

In case of very cold heavy weathered oils ("tar balls") which will not tend to support a water emulsion, the shredder may also be effective in chopping the product to a uniform particle size that can be suspended in the free water stream. The manufacturer has indicated that testing would be required to confirm this application. It should be noted that some types of pumps and skimmers, particularly "screw"-types, can process some debris themselves and could obviate the need for some in-line shredders.

Free Water Separation

Elimination of free water from the process stream will significantly reduce storage requirements, as well as heat requirements. Conceptual arrangements involve two custom-designed weir tanks for this purpose, with dimensions of a 20 foot ISO container and a capacity of about 32 m³. These two tanks could be connected either in series or in parallel. Free water would be drawn off the bottom continuously or intermittently, and discharged overboard into the boomed area so that any discharged oil would be recycled into the skimmer. For product which, with addition of emulsion breaker at the skimmer pump, can undergo emulsion breakdown with moderate heating, the two weir tanks might work more effectively in series. The first tank would eliminate free water, and then additional contact time in the second tank would separate water freed from the emulsion, further reducing the storage requirements. The separator tanks would be insulated to reduce heat losses.

Heating

Discussions with the distributors of IR heaters indicate that these units are not suitable for use in areas with a combustible or explosive atmosphere. Although glassed-in enclosures for these devices could be designed, the requirements to keep the glass clean and oil-free on a ship at sea could prove onerous. As such, IR heaters, though promising, cannot be recommended and a more traditional heat transfer media was chosen.

Hot circulating oil is recommended as a heating medium, using a source such as the Hi-R-Temp oil heater. One significant advantage of this approach is that the heater uses the same fuel as the vessel. The heater, fuel day tank and circulating oil expansion tank would be mounted in a 20" ISO container. These units are used routinely on black oil barges, and can be filled with gas detectors to shut down automatically in the event of explosive vapour atmosphere. In this application, a high, hinged intake for combustion air should be fitted to preclude drawing in vapours from adjacent storage tank vents.

Several panels of oil heating coils could be mounted in the top portion of the free water separation tank(s), to heat the oil flowing to the discharge while minimizing the amount of heat lost to the free water. For the anticipated collection rate of 25 m³ per hour for more viscous product, contact time in two parallel 32 m³ tanks would be approximately 2.5 hours. Initial heat transfer calculations indicate that a 10°C temperature rise could be achieved with two panel coils near the top of each tank and a heat input of 250,000 BTU/hr (75 kW).

Storage Tanks

Custom-designed, single shell storage tanks based on 20-foot and 40-foot ISO hi-cube (2.9 m high) container dimensions with approximately 32 and 64 m³ of storage respectively are recommended. This allows for road transportability, fast loading at a container facility and ease of lashing. Each transverse (athwartships) row of tanks would be lashed together into a block using standard bridge lock fittings, and the outboard units lashed to the deck with chain binders in the conventional manner. The eight foot (2.5 m) width dimension will minimize the free surface effect on the vessel's stability. Some transverse swash bulkheads should also be fitted in each tank to prevent the liquid sloshing along the length of the tanks.

One tank of each dimension would be fitted with a through manifold pipe, for connection fore-and-aft to a pump skid. Each tank would have a recess at the aft end for a transverse manifold pipe and a branch valve to the tank. Couplings between manifold sections would be made up as the units are loaded and lashed. All tanks should be insulated.

The tanks would be designed with external stiffening for ease of cleaning. Large cleaning hatches, small inspection/sounding hatches, and folding handrails could all be installed flush with the top dimension of the container. The tanks, particularly the 40' units, would probably not be designed to be lifted when full.

Additional heating coils and air sparging lines may also be installed in each storage tank.

Air Sparging

Air sparging pipes should be fitted to storage tanks that could contain oil that could gel. The spargers would be operated only when their use would not hinder separation of free or emulsified water or encourage additional emulsification. For tanks containing pure oil they

could be operated continuously to prevent gelling and encourage heat transfer. For other situations they could be operated for only short periods prior to pumping out the tank. The air requirements for each 20' or 40' ISO hi-cube would be about 18 or 36 m³/min (650 cfm or 1300 cfm) respectively. Since this can offer a simple, effective mixing regime and since compressors are easily rented as required, the installation of air-sparging lines in the bottom of each storage tank is recommended. Care must be taken to provide each sparged tank with a high vent fitted with a flame arrestor.

Transfer Pumps

Pumps must be simple, versatile, and capable of passing shredded solids. A hose or peristaltic pump is recommended. When fitted with a diesel driven hydrostatic transmission, they can handle a wide range of product viscosities at variable rates. The hydrostatic transmission can overcome the high starting torque experienced with this type of pump. For transfer from the water separator tank outlets to the storage tanks, a variable speed will be required to maintain the proper level in the weir tanks.

Two or more pumps, together with the diesel drive engine, hydraulic system and large diameter suction and discharge manifolds, can be mounted on one 20-foot ISO flat rack (Figure 1). Other devices, such as a pour point depressant injector, an annular water injector and a low pressure water flushing connection from the vessel's firemain, can also be incorporated into the manifolds on this skid.

The manifolds would connect to the storage tanks with a simple main/branch modular piping arrangement, used for both fill and discharge. The same pumping capability would be used for both transferring from the water separating tanks to the storage tanks and for discharging product through a floating hose to tankers. Heat tracing and insulation of all piping, manifolds and valves is recommended.

A single four inch (100 mm) pump, used in an intermittent application where extended hose life is not a concern, can pump 45 m³/hr at 50 m (520 kPa) discharge head with an input of 20 hp. Higher heads, up to 150 m (225 psi), can be produced at lower pumping rates. Two pumps should discharge the anticipated total storage volume of a larger vessel (400 m³) through a six inch (150 mm) hose in 4.5 hours. This could be accomplished during hours of darkness when recovery operations are not possible.

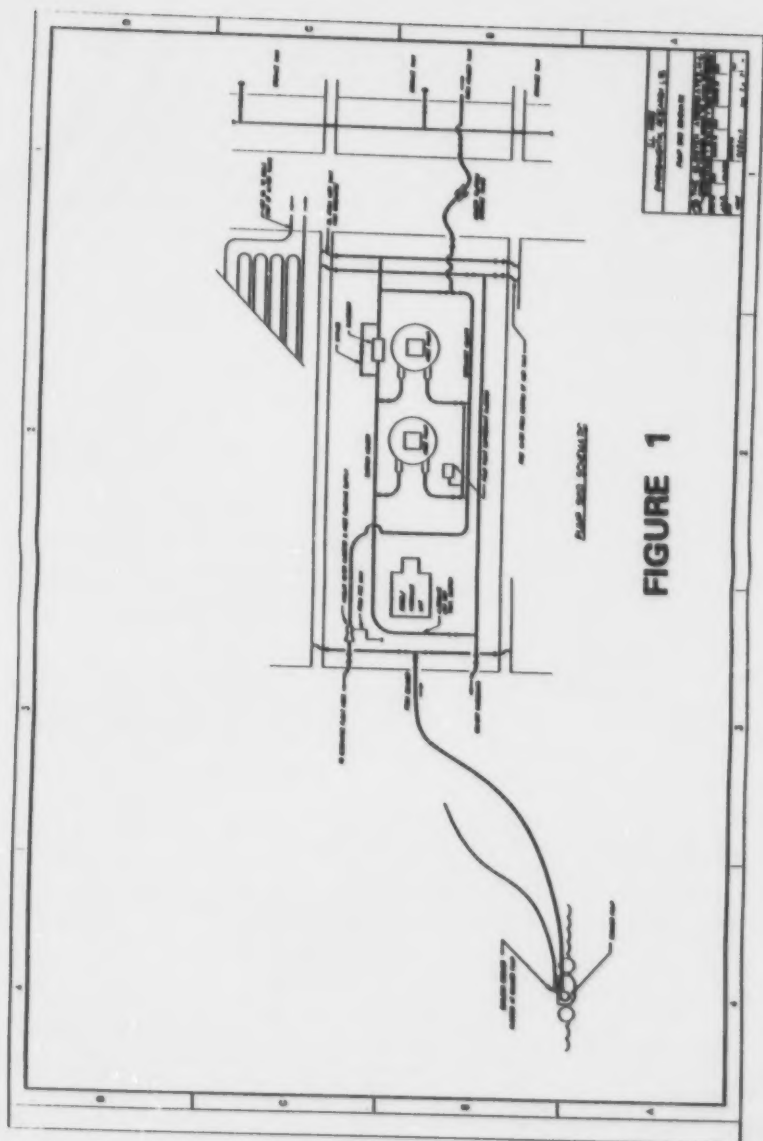
Alternatively, more traditional, higher capacity offloading and viscous service pumps (such as the Framo TK-series, Moyno, Thune Eureka, etc.) could be used if shorter pump times are desired.

Drag Reducing Agents

Drag reducing agents only function when the fluid flow is turbulent i.e., the Reynolds number, N_{RE} , exceeds 2100. For the range of oil viscosities and transfer flowrates in the scoping analysis (20,000 to 200,000 cP and 22 to 1070 m³/hr) the Reynolds number for a 6" hose ranges from 0.2 to 129. Therefore, drag reducing agents would not be effective.

Annular Water Injector

Probably the single most effective piece of equipment for drag reduction purposes is the annular water injector. A 60 m³/hr version was designed by CEDRE in France. This version was designed for a 6" feed pipe and a 4" discharge with a 1½" water feed line. It



weighs about 120 kg and nominally consumes between 3 and 6 m³/hr (25 and 50 L/min) of seawater. Based on the test-loop results reported in Peigné and Cessou 1989, the pressure drop for pumping a viscous fuel oil along 14 m of 4" hose at 80 m³/hr decreased from 1800 kPa to 300 kPa with a 6% water flow (80 L/hr.)

Hose Coatings

Because the likely flow regime is laminar, hose coatings would have no effect on fluid drag forces. Although they may be useful when cleaning equipment, their further consideration from the perspective of drag reduction is not justified.

OVERALL SYSTEM LAYOUT

COMPONENT COMBINATIONS

Figure 2 shows the proposed flow schematic for the recommended system. As the oil/water mixture enters the skimmer it is treated with 250 ppm of emulsion breaker using the inert gas delivery system and a hose twinned with the hydraulics for the skimmer. The skimmer discharge hose connects to an in-line shredder/manifold combination which reduces entrained solids to pumpable sizes and imparts additional mixing energy to promote emulsion breaking.

Free (and perhaps some emulsified) water is decanted in the 32 m³ (20' ISO container-sized) separators and the oil/emulsion is heated up about 10°C by panel coils. These coils are, in turn heated by a 75 kW (250,000 BTU/hr) diesel-fired hot oil system. This heating promotes further emulsion breaking and prepares the oil for pour point depressant addition.

On exiting the separators, the oil is treated with 100 ppm of pour point depressant, passed through another shredder and then pumped to 20' or 40' ISO container-sized storage tanks. These tanks are fitted with swash baffles; have bottom drains to decant water; contain panel coils for heating and are fitted with air sparging lines for gentle mixing and flame arrested vents.

When required, the transfer operation involves pumping from the storage tanks to a tanker or barge through 6" floater hose. This hose is stored on deck reels between transfers. Two peristaltic pumps can transfer 45 m³/hr each of fluid against a 50 m (520 psi) head. The transfer hose is also fitted with an annular water injector to reduce drag and pumping head when transferring more viscous products. Provision is made for ship's fire water to purge the system.

VESSEL DECK LAYOUT

Contacts were made with Arctic Transportation Limited and Secunda Marine Services Limited to obtain data on representative vessels. The following are some representative characteristics:

Triumph Sea and Terra Nova Sea

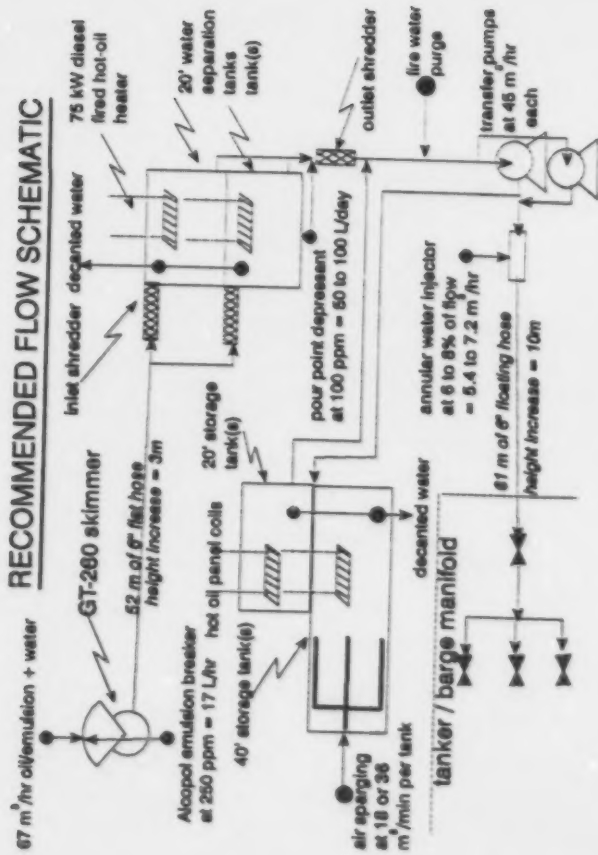
Dimensions:

Length 64.4 m

Breadth 13.8 m

Deck Load:

FIGURE 2



Capacity 800 tonnes
 Clear width 11.0 m
 Clear length 38.5 m

Arctic Ivik

Dimensions:

Length 67.4 m
 Breadth 14.0 m

Deck Load:

Capacity 1000 tonnes
 Clear width 10.7 m
 Clear length 37.2 m

The quoted deck cargo capacities are generally limited by stability and so are sensitive to vessel breadth, height of the load above deck, longitudinal position of the load, free surface moment, and condition of other load items such as fuel and water. The vessels' Trim and Stability Booklets must be consulted in each case.

The deck layout (Figure 3) has been prepared using the Arctic Ivik as an example, since plans of this vessel existed in Glostien Associate's CADD library. This shows the arrangement of the major components discussed above. The approximate weight of components and contents would be:

Modules:

Two weir tanks @ 2.5t	5.1 t
Oil heater	4.7 t
Pump skid	1.5 t
Skimmer crane	7.8 t
Skimmer cab	1.2 t
Skimmer and drive	3.0 t
Hose reel	1.2 t
Discharge hose reel	1.2 t
4-20" tanks @ 2.5 t	10.0 t
4-40" tanks @ 4.5 t	18.0 t
Air compressor (600 cfm)	<u>4.0 t</u>

Total empty weight 57.7 t

Contents @ sp.gr. = 1.0

Two weir tanks	64 t
4-20" tanks	140 t
4-40" tanks	280 t
Misc fuel & liquids	<u>6 t</u>

Subtotals liquids 490 t

Total deck load 548 t

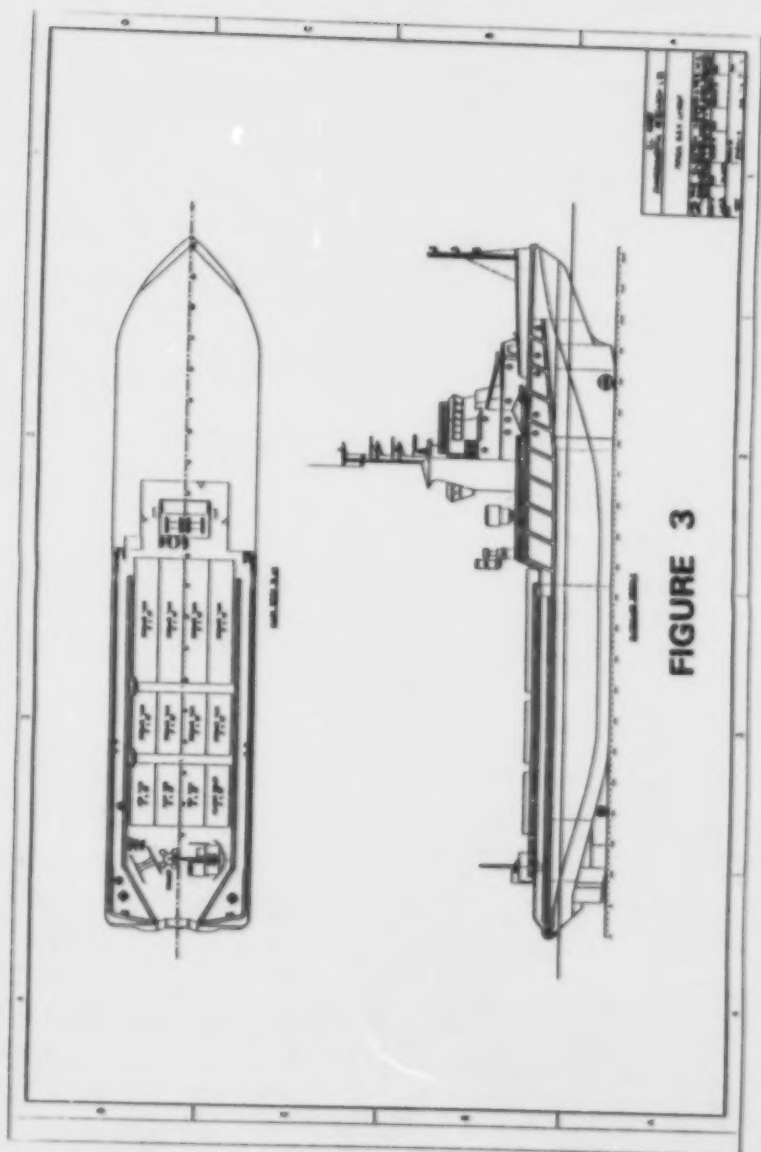


FIGURE 3

The loaded vertical center of gravity would be about 1.4 m above deck. Thus the space and deadweight constraints appear to be reasonably consistent using the proposed arrangement.

This deck layout provides a storage capacity of about 400 m³ (excluding the weir tanks). This would be sufficient for 9-16 hours of operation of a GT-260 skimmer, assuming free water is decanted.

CONCLUSIONS

1. The most promising viscosity reduction methods, suitable for use in an "vessel-of-opportunity" temporary storage and transfer system are:
 - * the use of emulsion breakers at the skimmer; this could reduce fluid viscosities by factors of 10 to 100
 - * shearing recovered oil and stored oil
 - * the warming of recovered oil; this will encourage emulsion breaking as well as reducing bulk oil viscosities.
 - * the injection of pour point depressants into warmed oil; this will reduce bulk viscosities in addition to lowering yield stresses and pour points.
2. The only drag reduction method suitable for use in a "vessel-of-opportunity" temporary storage and transfer system is:
 - * annular water injectors; these could reduce pressure drops in transfer lines by factors of 10-15.
3. The most promising methods to ensure a continuous flow of fluid in storage tanks to pump suctions are:
 - * heating the oil to a temperature above its pour point
 - * the addition of pour point depressants to warmed oil
 - * gently agitating storage tanks with air just prior to transfer operations
4. The most promising combination of methods to achieve temporary storage and transfer of recovered Grand Banks crude oils and their emulsions involves:
 - * direct injection of emulsion breaking chemicals into the skimmer mouth
 - * subsequently shearing the recovered fluid (and debris) with a grinder
 - * separation of free and any emulsion water in ISO-container sized separators on deck.
 - * heating of the oil/emulsification stream in the separator using panel coils supplied with hot oil from a diesel-fired portable heater
 - * injection of pour point depressants into the warmed oil/emulsion stream exiting the separators and subsequent mixing with an in-line grinder
 - * storage of the separator product in 20-foot or 40-foot ISO container-sized insulated storage tanks.
 - * continued heating of the stored oil/emulsification and decanting of water
 - * air sparging of the storage tanks continually (to encourage heat transfer if oil only is in tanks) or just prior to pumping out the tank
 - * use of an annular water injector downstream of the transfer pumps.

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IN-SITU BURNING OF EMULSIONS: THE EFFECTS OF VARYING WATER CONTENT AND DEGREE OF EVAPORATION

by

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Abstract

A series of experiments has been conducted to study the effect of water content, evaporation, thickness of the emulsion layer and environmental factors on the burn efficiency of Statford crude oil and emulsions. The experiments were conducted on Spitsbergen, in basins excavated in sea ice.

This paper presents the results from the experiments and, in additions some preliminary results concerning the dynamics of burning emulsions, and the efficiency of conventional and novel igniters.

Water-in-oil emulsions with a water content of 40% could be burned. However, conventional gelled gasoline was not a very effective igniter. Ignition success was improved when gelled crude oil was used as an igniter. The results imply that, for practical in-situ burning, the igniter technology needs to be improved.

INTRODUCTION

In-situ burning of oil is considered to be one of the most promising techniques for rapid removal of large quantities of oil at sea, particularly in ice infested waters. Most research that has been done until now deals with burning of fresh or unemulsified oil (Fingas and Laroche 1990). However, some studies have dealt with in-situ burning of emulsions (e.g. Buist 1989; Buist and Potter 1983; Twardus 1980). Oil at sea tends to emulsify and after one day the water content can be as high as 70% (Daling and Johansen 1986). If in-situ burning is to be a practical and efficient measure against spilled oil at sea, more concern has to be given to the burning of emulsions. If emulsions can not be burned in-situ, burning will be limited by a response time of only a few hours. NOFO (Norwegian Clean Seas Organization) has initiated a program to improve oil spill contingency for ice infested waters, especially directed to the forthcoming oil drilling activities in the Barent Sea. As part of this program a project on in-situ burning is going on. The results presented in this paper are a portion of the results that were obtained during one project dealing with burning of emulsions.

The objective of this project was to study how burn efficiency is influenced by:

- 1) The degree of evaporation of unemulsified and emulsified oil;
- 2) Water content in emulsions;

- 3) The combined effect of the degree of evaporation and water content; and
- 4) Film thickness of fresh and emulsified oil.

MATERIALS AND METHODS

The experiments were conducted on the frozen fjord next to the SINTEF laboratory on Spitsbergen in late winter 1991 (April-May). The burn experiments were conducted in circular basins (4 m²) that were cut in sea ice in Van Mijenfjorden. To maintain a constant water level an overflow system was made for the basins (Figure 1). The results presented below were obtained in 25 test turns (Table 1).

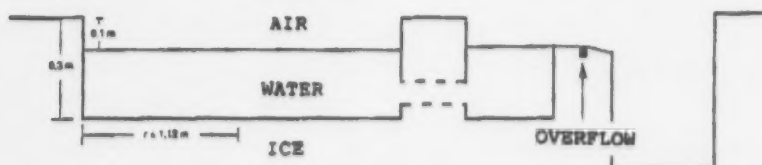


Figure 1. Overview of the constructed basins that were used in the experiments. The basins were evacuated in the sea ice, and comprised both a major test basin and an overflow system to maintain a constant water level.

Table 1. Summary of the experimental oil and emulsions burned.

Exp. Series	Oil Type	Water content (%)	Amount of oil/emulsion (liters)
I	Crude, 150+ - 300+	0	32
II	Crude, 150+ - 250+	0	32
III	Crude, 150+ - 250+	0	16
IV	Crude, 150+ - 250+	10	32
V	Crude, 150+ - 250+	20	32
VI	Crude, 150+ - 250+	40	32

Test oils

Oil from the Statoil refinery (Mongstad) was used in the experiments. The test oils comprised:

- a mixture of Statfjord and Gullfaks (4:1)
- 150+ (18% evaporated oil)
- 200+ (28% evaporated oil)
- 250+ (37.5% evaporated oil)
- 300+ (45.5% evaporated oil)

The weathered oils were characterized as mixtures of different petroleum products:

- heavy naphthalene (HN)
- kerosene (Kero)
- light gas oil (LGO)
- heavy gas oil (HGO)
- buffercut
- residue

The composition of the test oils are given in Table 2.

Table 2. Composition of the test oil used in the experiments, and for the mixing of emulsions.

Oil Type	HN	Kero	LCO	HGO	Buffercut	Residue
Crude	4.6	11.9	14.8	7.0	5.0	30.5
150+	6.2	16.1	20.1	9.5	6.8	41.3
200+	-	17.2	21.4	10.1	7.2	44.1
250+	-	-	25.8	12.2	8.7	53.3
300+	-	-	-	16.5	11.7	71.8

Physical and chemical properties

Oil density was determined with an Anton Paar densitometer, model DMA 35. Viscosity was measured with a Brookfield DV-II viscosimeter (Shear rate 10 s⁻¹, UL adapter). Distillation data were obtained from the Mongstad refinery. The physical and chemical properties of the oils are given in Table 3.

Table 3. Physical and chemical properties of the test oils used in the experiments and for mixing the emulsions.

Oil Type	Density (g/ml)	Visc. (13 °C) [cps]	Initial Boiling Point [°C]	Vol % Dist
Fresh crude	0.846	10.9	n/d*	-
150+	0.881	102	134	18
200+	0.883	87.7	193	28
250+	0.902	429	241	37.5
300+	0.921	n/d*	256	45

* n/d = not determined

Mixing of emulsions

Emulsions were made by mixing sea water and oil in the desired proportions. Maximum batches made each time were 64 liters. Oil and water were circulated through a gear pump (1450 rpm) until stable emulsions were created. Emulsion mixing time ranged from one to six hours depending on oil type and the amount of water.

RESULTS

Igniters

Initially, 400 ml of gelled gasoline (50 g Surefire/2000 ml gasoline) was used as an igniter. However, as the test burns proceeded, limitations with this mixture were found. In order to provide successful ignition of the most evaporated, and emulsified oils, alternative ignition sources were developed and tested. These were:

- gelled diesel
- liquid and gelled crude oil

Special attention was given to the gelled and liquid crude oil. Some measurements of flame temperature were done with a Termovision 400 Infrared Camera (Agema Infrared Systems AB), showing that crude oil burned with nearly twice the temperature of gasoline. The measured flame temperature for gasoline was about 1000°C, while for crude oil the temperature in the flames was approximately 2000°C. This may be due to the wider range of compounds in crude oils, particularly those with higher boiling points than found in the gasoline. Diesel gave a flame temperature in the middle between that found for gasoline and crude oil. In the burn tests gelled gasoline worked well with unemulsified oils but for the emulsions with 28% evaporation, and more than 20% water content, it was necessary to use gelled or liquid crude oil.

Burning of unemulsified oils

Three series of experiments with unemulsified oils were conducted (Table 1). In the experimental series I and II the initial film thickness was 8 mm, while in series III the thickness was 4 mm. Figures 2-6 present the results from these experiments.

Burn efficiency

Figure 2 gives the burn efficiency for the unemulsified oils. Burn efficiency was related to the degree of evaporation and the initial film thickness of the oils. In the two experimental series with 8 mm film thickness the burn efficiency for all the oils with evaporation of less than 45% ranged between 80 and 90%. In the burns with 45% evaporated oil the burn efficiency decreased to approximately 70%. In the experiments with 4 mm film thickness, oil burn efficiency was approximately 80% for the fresh crude and the 20% evaporated oils. For the 28 and 38% evaporated oil, the burn efficiency decreased to 70% and 30%.

Extinction film thickness

The extinction film thickness was estimated from the volume of residue and the oil-covered area at extinction. Estimated extinction film thickness for the three experimental series are given in Figure 3. Within each of the three experimental series the extinction film thickness tends to increase with increasing degree of evaporation.

In all the experiments with fresh crude oil the extinction film thickness was between 0.6 and 0.7 mm. When the oil burned was 20% evaporated a slight increase in film thickness was found.

In the experiments with 8 mm initial film thickness and a 45% evaporated oil, the extinction film thickness was approximately 2.5 mm, the same thickness which was estimated for the burn with 4 mm initial film thickness and 40% evaporation.

Ignition time

The ignition time (i.e. time before the oil caught fire close to the igniter) is given in Figure 4. Fresh crude oil ignited instantaneously. When the oil was 18% evaporated or more, a delay in the ignition time was found. Except for the second experiment (with higher wind velocity - shown as open circles in Figure 4) with 37.5% evaporation and 8 mm initial film thickness all the oils were ignited after less than 90 seconds. For 4 mm initial film thickness ignition time was at the same level as for the 8 mm initial film thickness (Series I), for all the degrees of evaporation.

Flame spreading

The flame spreading is given in Figure 5. Except for the burn series conducted with high wind velocity, (open circles in Figure 5) evaporation results in reduced flame spreading rate. The flame spreading for fresh crude was approximately three times faster compared to the more evaporated oils.

Regression burn rate

The regression burn rate generally decreased with increasing degree of evaporation (Figure 6). In the burn with high wind velocity (open circles) this tendency was not clear. The burn rate for the fresh crude varied between 1.8 and 3 mm/min while for the evaporated oil, the burn rate was lower, between 1.2 and 2 mm/min.

Burning of emulsified oils

Three series of experiments with emulsified oils (10, 20 and 40% water content) were conducted (Table 1). In the experimental series IV and V the initial film thickness was 8 mm. In series VI (40% water) the thickness was increased to improve ignition success. Figures 7-11 present the results from these experiments.

Burn efficiency

Burn efficiency is given both as the percentage of emulsion removed (Figure 7) and the percentage of oil removed (Figure 8). The experiments with 10 and 20% water were done with an initial film thickness of 8 mm. In the burns with 10% water (closed dots), the burn efficiency was not affected by the degree of evaporation. The burn efficiency was approximately 90%. For the 20% emulsion (open dots), the burn efficiency was high, approximately 90%, when the oil from which the emulsion was made from either fresh oil, or 18% evaporated. For the 28 and 37.5% evaporated oil, the burn efficiencies decreased to about 80 and 60% respectively. The burn efficiencies for these emulsions (10 and 20% water), was approximately the same as that found for the unemulsified oil (Figure 2).

In the experiments with 40% water-in-oil emulsions (filled squares), attempts were made to ignite the oil with an initial film thickness of 8 mm, but only the emulsion made from fresh crude could be ignited. The emulsion with the 18% and 28% evaporation were ignited and burned when the initial thickness was increased to approximately 40 mm. The resulting burn efficiency was on the same level as that found for the 10 and 20% water emulsions. The emulsion with 37.5% evaporation ignited when the initial thickness was increased to 32 mm; however, the burning was not sustained and only a little part of the emulsion was removed.

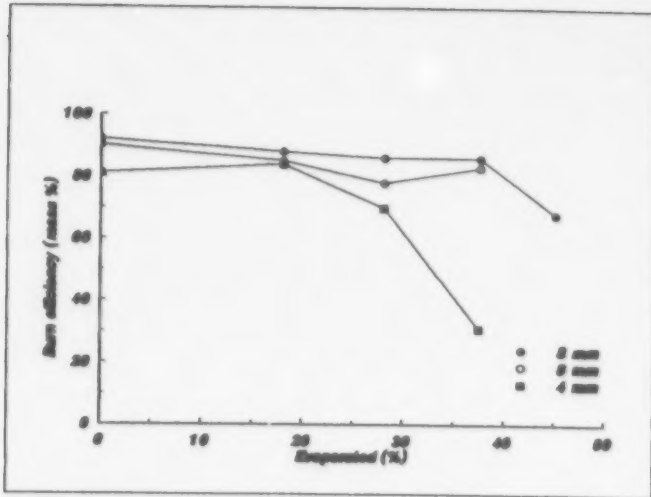


Figure 2: Burn efficiency of unemulsified oils plotted against the degree of evaporation

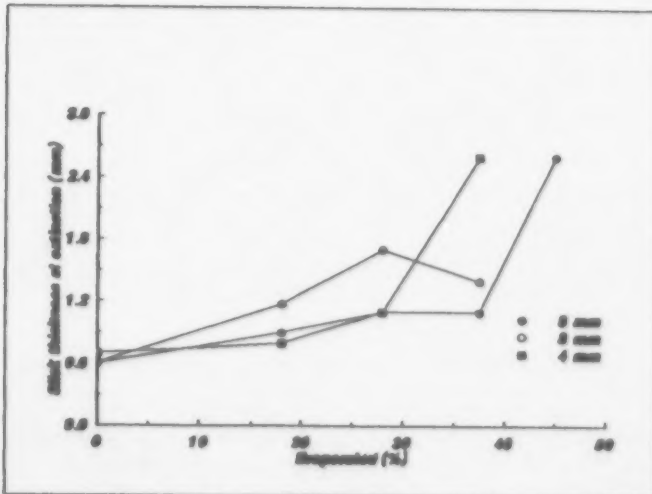


Figure 3: Extinction thickness of unemulsified oils plotted against the degree of evaporation

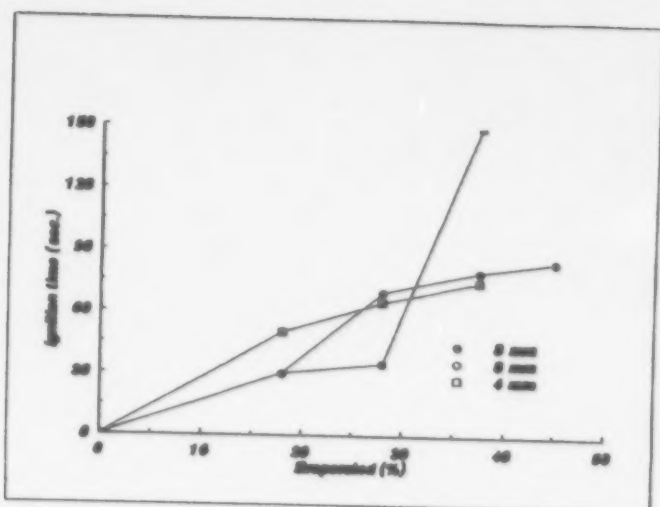


Figure 4: Ignition time of unemulsified oils plotted against the degree of evaporation

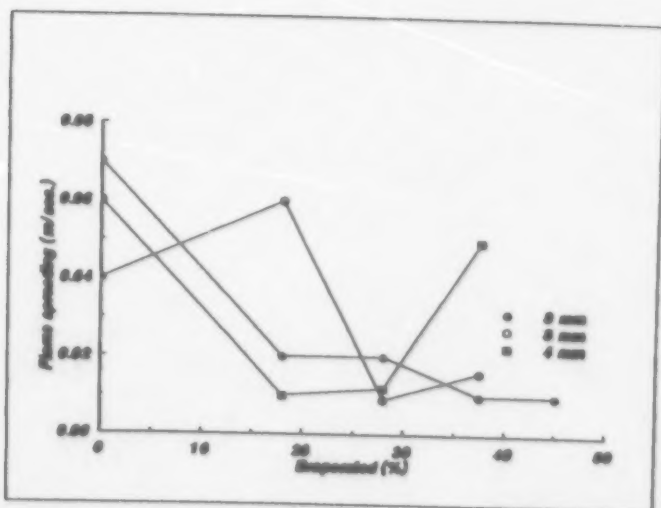


Figure 5: Flame spreading rate of unemulsified oils plotted against the degree of evaporation

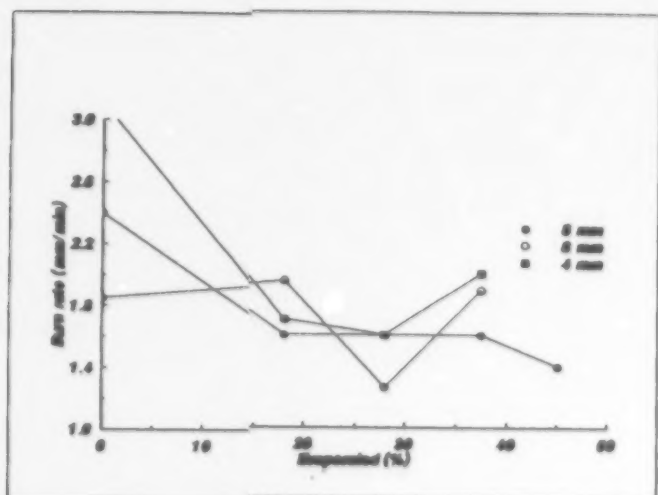


Figure 6: Regression burn rate of unemulsified oils plotted against the degree of evaporation

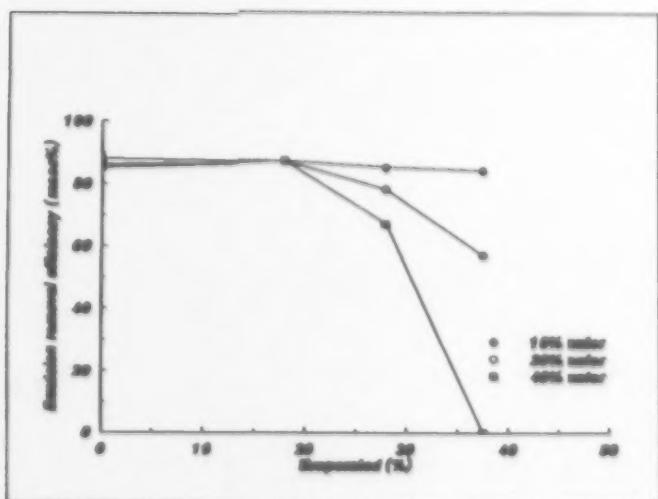


Figure 7: Burn efficiency of emulsified oils plotted against the degree of evaporation and based on the removal of the emulsion

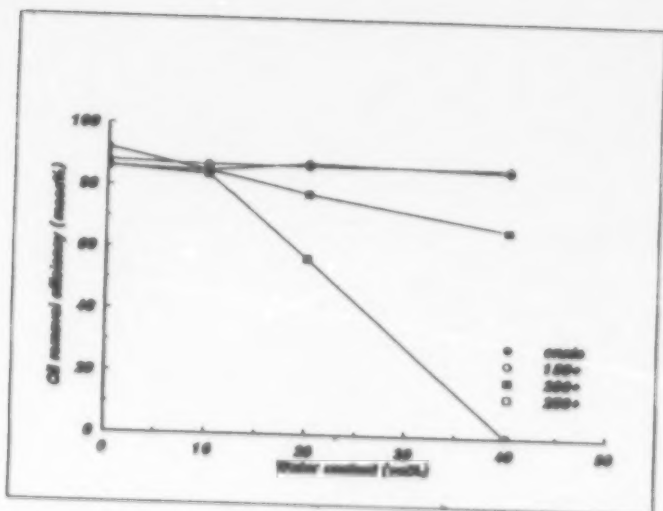


Figure 8: Burn efficiency of emulsified oils plotted against the water content of the emulsion and based on the removal of the oil

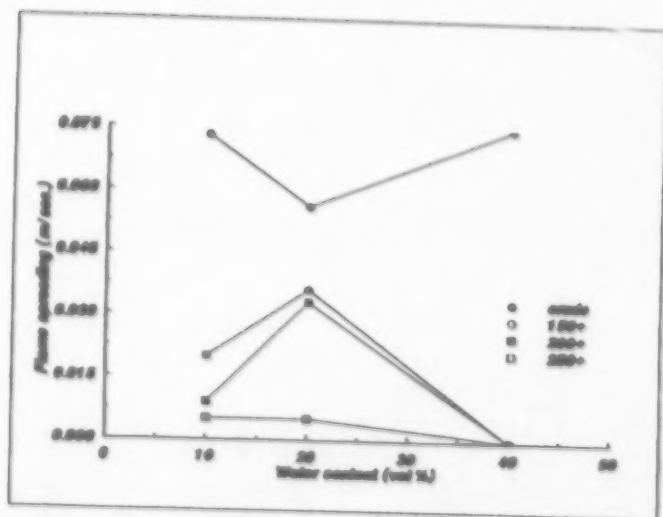


Figure 9: Flame spreading of emulsified oils plotted against the water content of the emulsion

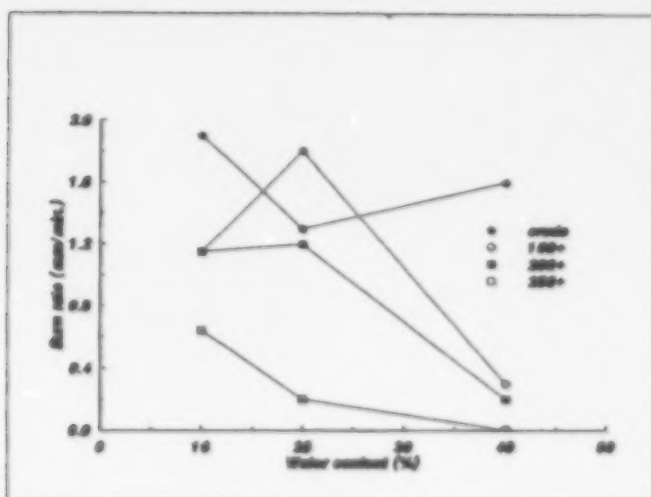


Figure 10: Regression burn rate of emulsified oils plotted against the water content of the emulsion

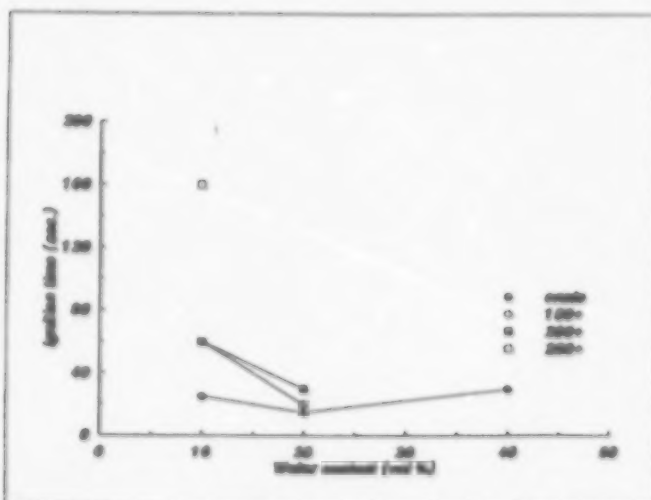


Figure 11: Ignition time of emulsified oils plotted against the water content of the emulsion

Flame spreading

The flame spreading rate (Figure 9) decreased when the degree of evaporation of the emulsions increased, and when the water content increased. For the emulsions made from fresh crude oil, the flame spreading was much faster than for the emulsions made from evaporated oils, i.e. approximately four times faster than for the emulsions made from 18 and 28% evaporated oil. The flame spreading of the 37.5% evaporated oil was very slow, and close to zero, when the water content was 40%.

Regression burn rate

The regression burn rate (expressed as mm of emulsion removed per minute) for the emulsions is given in Figure 10. The rate for the emulsions made from fresh crude oil varied between 1.3 and 2.0 mm/min. Both the 18% and 28% evaporated emulsions with water content up to 20% burned with rates on the same level. Emulsions blended from the same two oils, but with 40% water, and all the emulsions made from 37.5% evaporated oil, had much lower burning rates, in the range slightly above zero up to 0.6 mm/min.

Ignition time

The ignition time for the emulsions is given in Figure 11. The ignition time increased with increasing degree of evaporation. The emulsion made from crude oil ignited after approximately 25-30 seconds. The ignition time for the 18% and 28% evaporated oil with 10 and 20% water was longer, up to about 60 seconds. It was not possible to ignite the emulsions made from the 18 and 28% evaporated oils with 40% water content with the gelled gasoline.

DISCUSSION

In-situ burning of emulsions differs from burning of unemulsified oil. The controlling process seems to be the removal of the water in the emulsions. We can assume two different modes for this:

- By boiling the water out; or,
- By breaking the emulsion thermally or chemically.

In our studies we have no indications that the emulsion is broken thermally, and the process outlined in this is based on observations that water is evaporated from the emulsion layer. When the water is boiled out, oil is released and forms a layer on top of the emulsion layer. The amount of oil that is released and the rate of release probably depend on the water content of the emulsion. With higher water contents, the amount of heat required to leave a certain amount of oil, increases. If the water content is f_w , then the amount of oil that can be released (f_o), is $1-f_w$. The required heat for the release of f_o is thus the heat required to evaporate f_w from the emulsion. When the oil layer is created on the emulsion layer, the oil will be volatilized by the radiated heat and when its temperature reaches the fire point of the oil it will ignite. The temperature in the oil depends both on the added heat, and the thermal properties of the oil, emulsion and the underlying water. If the thermal conductivity of emulsions is lower than for water, the oil layer required on the top of the emulsion layer may be thinner than that necessary to ignite the same oil directly on water.

In order to ignite an emulsion, the igniter needs to have certain properties:

- It must burn long enough, and with enough heat to create an oil layer on top of the

- emulsion, which is thick enough to burn and then ignite the layer.
- Ignite oil in an area that is big enough to ensure a self sustained burn.

In terms of ignition success, all the unemulsified oils (fresh crude to 45% evaporation) could be easily ignited with the available gelled gasoline technology. As long as the initial film thickness is high, i.e. approximately 8 mm, the oils will burn with an efficiency of 70 - 90%. For the most evaporated oils, low initial film thickness gives efficiencies below this (e.g. 37.5% evaporation, 4 mm film thickness burned with only 30% efficiency).

Emulsions can be burned; however, for oils evaporated more than 18%, and with a water content of more than 20%, the gelled gasoline is insufficient as an igniter. Gelled or liquid crude oil proved to be a better igniter for the emulsions. With crude oil it was possible to ignite emulsions with 40% water, and 28% evaporation provided that the initial film thickness was high enough. Successful ignition and burning of oils and emulsions required good flame spreading. With heavy oils and emulsion this is only possible if the igniter either itself covers an area that is big enough to continue burning, or somehow promotes flame spreading across the slick surface.

CONCLUSIONS

- 1) Ignition time for unemulsified crude oil, increases with increasing degree of evaporative loss. Fresh crude ignited instantaneously while the most evaporated oils needed more than one minute to be ignited.
- 2) For unemulsified oils the flame spreading rate decreases as the evaporative loss increases.
- 3) The regression burn rate decreased as the evaporative loss increased, and varied between 3 and 1.5 mm/min.
- 4) Burn efficiencies for oils with maximum 37.5% evaporation were on the same level (approx. 90%). With higher evaporative loss and low initial film thickness, burn efficiency was drastically reduced.
- 5) The extinction film thickness increased with increasing evaporative loss and varied between 0.6 (fresh crude oil) and 2.8 mm (45.5% evaporated).
- 6) Ignition time for emulsified oil increases with the degree of evaporative loss of the oils from which the emulsions were made.
- 7) When the water content varied between 10 and 40% the emulsions made from fresh crude were ignited after approximately 25 seconds. Emulsified 18% evaporated and 28% evaporated fractions were more difficult to ignite. The emulsified 18% evaporated fraction (40% water) could not be ignited with gelled gasoline without increasing the film thickness to approximately 40 mm. The emulsified 28% evaporated fraction (40%) did not ignite with gasoline but did with gelled crude oil. It was not possible to ignite the emulsified 37.5% evaporated with 40% water.
- 8) For the emulsions the flame spreading rate decreased with increasing degree of evaporation in the parent oil and with increasing water content. When the emulsions were made from fresh crude oil no relation between flame spreading and water content was found. For evaporated oil with 40% water content the flame spreading rate was approximately zero.
- 9) The emulsions with the lowest water content and the lowest degree of evaporation had higher burning rates than the more heavy emulsions.
- 10) For the removal of emulsions the effect of evaporation was greatest when the water content was high (40%); between 70 and 90% of the emulsion was removed when the degree of evaporation was up to 30%. Only 12% was removed when the degree of evaporation was 40%.
- 11) Emulsions can be ignited and burned; however, gelled gasoline is not the best igniter; a system that burns longer, hotter and spreads to cover a larger area would be an improvement.

Acknowledgements

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Measurement of Volatiles, Semi-volatiles and Heavy Metals in an Oil Burn Test

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1. Introduction

In-situ burning is one of the many countermeasures to combat oil spills. The primary advantage of burning is rapidity: in some favourable cases it can remove as much oil in one day as would be removed in one month by mechanical removal. Damage to shoreline and biota can thus be minimized. In addition it requires much less equipment and man-power resources. In remote areas where the logistics of cleanup equipment is insurmountable, in-situ burning may be the only practical means of oil removal.

On the other hand, burning produces large volume of smoke and, until there is a clear understanding of the constituents of the emitted smoke/soot and the remaining residue, in-situ burning is not likely to win public acceptance.

In view of this, a consortium of over 15 agencies in the US and Canada have joined forces to study burning and are actively planning to conduct large scale experiments. As part of this effort, a meso-scale burning exercise was carried out during April-June 1991 at Mobile, Alabama. Two preliminary and eleven burn tests, each with 2000-5000 gallons of crude oil, were conducted at the facilities of Fire and Safety Test Detachment at Sand Island situated at Upper Mobile Bay. A variety of parameters that might affect burning and smoke production were tested. During each burn, extensive samples were taken from the oil, residue and the smoke plume itself. In addition to ground station samplers, air-borne samplers were also employed. The analytical parameters include volatiles and semi-volatiles of environmental interest, and heavy metals typically contained in the starting crude oil.

In this paper, the detailed analytical work employed to analyze the burn samples is outlined and discussed. Real-time CO₂, SO₂ particulates and benzene/toluene/ethyl-benzene/xylene (BTEX) measurements were carried out by REAC, an EPA contract lab. The limited scope of this paper does not cover the results of those tests.

II. Experimental

SAMPLING

A layout of the site with schematics of sampling equipment is shown in Figure 1. The burn was conducted in a specially-constructed open steel pan (51x51 ft) with an outer perimeter filled with water. In a typical burn, 2000-gallons of Louisiana crude was released on about 3 feet of water. The oil was ignited and the burn generally lasted about 15-20 min. Details of the major sampling apparatus are described below:

Polycyclic Aromatic Hydrocarbon (PAH):

AirCon air samplers (Gilian) were used at 50 feet upwind, 100 and 200 feet downwind from the burn pan. The pumps were operated at a nominal flow rate of 10 L/m. Air was draw through a 37-cm 2- μ m TFPE filter, followed by a 8x110 mm size XAD sorbent tube. Typical sample volume was 100 L.

Cumulative samples for PAH analysis were also taken at two downwind locations throughout the duration of the burn project. Sampling media was the same as standard PAH method. The cumulative sample volume was typically 1400 L.

Aliquots of fresh crude and burnt residue were taken before and after each burn. The water in the burn pan was also sampled before and after the burn for PAH and metal analyses.

Volatile Organic Compound (VOC):

Gilian HFS-513 personal samplers were employed at the same location: sampling media was a two-stage coconut charcoal tube (8x110 mm, 600 mg) at a nominal flow rate of 2 L/m. Typical sample size was 50 L. Again, cumulative samples were taken at two downwind locations; sample size was an average 500 L.

Metals:

Heavy metals in soot were collected using Gilian personal samplers on a 37-cm, 0.8- μ m membrane cellulose ester (MCE) filter again at the same locations. Operated at 2 L/m, the pump collected a typical sample volume of 40 L.

C2-C12 VOC:

Whole air/smoke samples were taken using 6 L evacuated stainless steel canisters (Summa canisters, Scientific Instrumentation, Moscow, Idaho) at the 100 ft downwind location.

Polychlorinated dibenzo-p-dioxin/furan (DX/DF):

High volume samplers (PS-1, General Metal Works) were employed to collect cumulative samples at upwind and downwind locations. Sampling media were 4 in. glass-fibre filter followed by a 2x3 in. polyurethane foam plug (PUF). Flow rate was nominally 200 L/m; the cumulative sample volume was an average 70 cubic meters.

Together with the field samples, reagent blanks (unopened tubes) and trip blanks (opened tubes exposed to the atmosphere for the same duration as the samples) were also sent and analyzed with the samples.

III. Sample workup

PAH:

PAH samples from AirCons were initially extracted ultrasonically in toluene/acetone (95/5 %) in accordance with NIOSH method 5510 (ref 1). The front-half and back-half of the XAD tubes were extracted separately to determine the distribution of collected PAH. From the preliminary runs, it was discovered the soot loading was very small and the PAH was below detection. The tube was then extracted whole to lessen the work load and to improve the detectability of low levels of PAH.

Soxhlet extraction was later used when it was found out the ultrasonic extraction did not recover all the PAH from the sampling media. The filter/XAD was placed in a cellulose thimble and spiked with a mixture of four deuterated PAH compounds and extracted by toluene/acetone in a Soxhlet overnight. The raw extract was dried over anhydrous sodium sulphate and roto-evaporated and concentrated to 1 mL. A d12-terphenyl internal standard was added prior to GC/MSD analysis.

Crude and residue sample was first dissolved in cyclohexane to precipitate asphaltenes. An aliquot equivalent to about 50 mg of oil was spiked and subjected to silica column cleanup. The saturates were first eluted with hexane; the aromatic (PAH) fraction was eluted using benzene. This fraction was concentrated and the column cleanup was repeated to remove the residual oil. An internal standard of terphenyl was added prior to injection. Water samples were spiked and extracted 3 times by dichloromethane (DCM). The extracts were dried, combined and concentrated to 1 mL before instrumental analysis.

VOC:

The method was based on NIOSH methods 1003, 1500 and 1501 for

the analysis of VOC having boiling points below 200°C in air samples (ref 1). The charcoal tubes were extracted ultrasonically with carbon disulphide (CS₂), a mixture of 5 internal standards were added and the extracts analyzed by GC/MSD, using a mixture of 45 native VOC and 5 internal standards for calibration.

Metals:

Samples preparation and analyses were performed by Lab Services Division, Food Production Branch, Agriculture Canada, Ottawa. The MCE filter was first spiked with an internal standard of Be and Y at 2 ppm. It was then wet-ashed by a 10-mL mixture of concentrated nitric and perchloric acid (4:1) and the digested sample was taken up with 10 mL concentrated hydrochloric acid. Final volume was typically 50 mL.

Analysis and Quantitation

PAH analysis was carried out on a Hewlett Packard (HP) HP5890GC/5971A Mass Selective Detector (MSD). A 30 m DB-5 fused silica column (0.25 mm, 0.25- μ m film) was used to separate the PAH mixture. It was coupled directly to the MSD operated in Selected Ion Monitoring (SIM) mode. Oven temperature was 90°C/min, ramped to 180°C at the rate 20°C/min and to a final temperature of 285°C and held for 10 min at the rate of 7.5°C/min. A 1- μ L aliquot of sample was injected splitless on the GC using a HP 7673 autosampler. A minimum of two ions of each PAH was monitored with a dwell time of 50 ms on a PC-based data station using HP1034B software.

Initially, a Supelco 610M PAH mixture containing 16 PAH compounds was used as calibration standard. Later on, an expanded list of PAH was furnished by using a standard reference material SRM-1491 which has 24 compounds covering the methylnaphthalenes and methylphenanthrenes, which are important constituents of crude oils. Area response of the quantitation ion was corrected by that of the terphenyl internal standard; recoveries of the four surrogate PAH spiked onto samples were monitored to ascertain the integrity of sample during sample workup.

VOC analysis was performed also on the GC/MSD, using a Restek RTX-5 column (crossbonded SE-54 phase, 30-m x 0.32-mm, 0.5- μ m film) for separation of the 45 VOC compounds on the target list. Oven temperature was 30°C/3-min, to 150°C @ 4°C/min and to 220°C/1min @ 8°C/min. The MSD was operated in scan mode from 35-360 amu with a scan rate of 1 scan/sec. Characteristic ions were extracted from each analyte peak from an appropriate time window and the area response was corrected with the 5 internal standards co-injected with the sample.

An ARL 3510 ICP (Inductively Plasma Spectroscopy) was used to perform metal analysis. Calibration standard range was from 0-10 ppm.

C2-C12 VOC analysis was performed by Pollution Measurement Division, River Road Environmental Technology Centre, Ottawa. Approximately 1.2 L of sample air was pre-concentrated on a trap using liquid oxygen, at a sample flow of 40 mL/min for 30 min. The trap was heated up to 100°C, the VOC was backflushed into a GC/MSD. Peak identification was based on retention time as well as spectral matching against a NBS 49000-spectra library (Ref. 2).

Dioxin/furan cumulative samples were spiked with a mixture of ³⁷Cl-labelled DX/DF and soxhlet-extracted in toluene. The raw extract was cleaned using an acid/base-modified silica column, followed by fractionation on a basic alumina column. The DX/DF fraction was recovered using 25% DCM/toluene. Analysis was carried out on a medium/high resolution VG-70S sector GC/MS system, operated at a resolution of 6000 (Ref. 3).

IV. Results and Discussions

PAH in Air/Smoke Samples:

One of the primary objective of the burn study was to investigate the amount of environmentally significant pollutants generated, and could therefore provide basic input parameters necessary to assess the impact to the environment. PAH is known to be present in all combustion processes, and thus is a prime candidate for examination on any incineration process.

Upon reviewing the PAH data for ground samples, it became obvious that none of the filter/XAD samples had any PAH. The reason could be due to inadequate sensitivity of the method or insufficient sampling. Under the described experimental condition, the GC/MSD had a detection limit of 0.05-0.1 ng/ μ L (higher molecular weight PAH had poorer response due to discrimination by the splitless injector). This translated to a 0.1 μ g minimum detectable quantity of PAH per sample, assuming a final extract volume of 1-mL. A typical range of air/smoke sample volume in this burn study was 100-200 L. The overall method detection limit thus became 0.5-1 μ g/cubic meter (CM).

This would seem to be adequate for a typical smoke concentration of 20-330 μ g/CM, assuming a starting PAH concentration of 6000 ppm in the crude oil and a soot yield of 10%; concentration being dependent on the distance from the source (Ref.4). Examination of the exposed filter/sorbent tubes revealed that there was usually very little soot collected. The only plausible explanation for low PAH levels would be

errors in the sampling process. It turned out the location of the ground samplers were not ideal: the smoke plume did not always follow a trajectory that ran close to and parallel to the ground. In fact, for relatively calm days, the smoke plume was observed to angle upwards at a 20-40 degree angle, with the result that the smoke samples collected were not representative of the plume.

The airborne samplers, suspended in the smoke plume by blimps operated by NIST were at a better position. The blimps were manoeuvred in position and tethered to the ground at 100/200 feet locations. However, because of difficulty in manoeuvring the blimp once the burn commenced, coupled with the fact that the payload only allowed the use of low volume personal samplers, only a limited number of PAH runs were made. For those runs, the sampling duration was too short to provide a sufficient sample volume. To illustrate, in the preliminary burns conducted on April 16 and 17, one blimp sample was analyzed to have 4 $\mu\text{g}/\text{CM}$ of phenanthrene. This was barely above the method detection of 2.5 $\mu\text{g}/\text{cu m}$ because the sample volume was only 21 L. In the second run, the sample volume was even less at 12 L, but phenanthrene was detected at 12 $\mu\text{g}/\text{cu m}$, sufficiently above the detection limit of 4 $\mu\text{g}/\text{CM}$. These runs were collected approximately 100 ft downwind of the fire. The concentration, however, was still much lower than anticipated.

PAH in Crude and Residue Samples:

The double silica column cleanup coupled with GC/MSD analysis enabled detection of PAH in crude/residue samples down to 1 μg PAH/g. The chromatogram was almost free from oil background. Resolution of the anthracene/phenanthrene, benzo(a)anthracene/chrysene pair was maintained at 5% and 8% respectively, well within the EPA method 500 series chromatographic criteria (Fig.2). By far the most abundant PAH in the crude oil were the naphthalene and methylated naphthalenes, followed by methylphenanthrenes (Fig.3). The parent PAH were only minor constituents of the total PAH found.

Analyses of various aliquots of the crude taken on different days showed total PAH to be remarkably constant at around 5000 $\mu\text{g}/\text{g}$, with over 90% PAH made up of three rings or less. Residue samples also showed consistent PAH levels but at much lower concentration at about 500 $\mu\text{g}/\text{g}$, despite the different burn conditions and sampling conditions (Fig.4). The chromatograms of the before and after burn had more or less the same profile but depletion of lighter PAH was noticeable. The marked difference was the make-up of PAH: the three rings or less PAH now only constituted about 50% of total. This was consistent with earlier work, demonstrating that there was a shift towards higher-molecular-weight PAH in the residue in soot. The enrichment factor,

however, was only about 2 to 5 instead of 10-20 from bench-scale burn experiments (Ref.5) .

VOC:

Most of the charcoal samples showed appreciable VOC composed mainly of straight-chain hydrocarbons and BTEX. Total VOC ranged from a low of 100 to a high of 4000 $\mu\text{g}/\text{CM}$, with most of them in the 1000-2000 $\mu\text{g}/\text{CM}$. In some runs the 200 feet downwind station collected more VOC than the 100 feet one. This was undoubtedly due to the meandering path of the smoke plume. On one day there was even more VOC in the 50 feet upwind than downwind ones, which was believed to be due to ground turbulence or shift in wind direction.

VOC samples were not analyzed until a few months later after the burn (the recommended holding period is 2 weeks). Analyses of duplicate sample sets showed agreement to be about 25%. In a subsequent QA exercise, comparison with an EPA contract lab showed the range of VOC was largely comparable. Some samples arrived from the field with the protective caps loose, raising concern about the integrity of the samples.

Metals in Filters:

Of the 11 elements measured (Zn, Cd, Pb, Co, Ni, Hg, Mn, Fe, Cr, Mg and V), none were found to be much higher than the detection limit of 1-100 $\mu\text{g}/\text{CM}$. Comparison of the crude/residue oil metals results showed for some metals that there was a slight enrichment of metals in the residue by a factor of 2 to 4. QA studies conducted in-house using the digested samples between Agriculture Canada showed excellent agreement, generally within 10-20%.

Dioxin/furan:

The DX/DF level in the cumulative samples was very low: with about 1 pg/CM of DX and 0.1 pg/CM of DF. The only detectable DX isomer was the higher chlorinated hepta- and octa- species. The concentration and isomer distribution was typical of an urban atmosphere level.

C2-C12 VOC:

The summa canister samples revealed concentration and pattern of VOC consistent with open evaporation of oil products. There was no evidence of formation of new combustion products.

Novel Sampling technique:

This burn study marked the first successful deployment of remote-control (RC) helicopter for air sampling. The helicopter was based on a hobby RC 60-size helicopter extensively modified by incorporating a remote start Gillian pump and strobe light to signal proper operation of

the sampler. With a gross weight of 15 lbs, including a full tank of gas, the flight duration was 15-20 min and an operating range of about 500-1000 ft.

In this particular burn, a flight path was adopted to enter the plume at about 700 feet from the fire so as not to interfere with the blimp operation. As that point, the smoke density was significantly reduced and the recovered sample had just trace levels of PAH in it. Nevertheless, presence of methylnaphthalenes were detected, proving that the lighter PAHs were vaporised and carried sufficiently far downwind from the burn site. The blades were covered with soot at the end of the flight and were recovered using hexane-soaked swab. The swab was analyzed and had a PAH profile similar to that of the residue and, remarkably, relatively free from the anticipated background interference. This pointed to the interesting possibility of a passive sampling device in future work.

V. Conclusion

An extensive sampling exercise was carried out to sample the pollutants in the smoke plume from a meso-scale in-situ burn experiment. Because the smoke plume did not always impinge on the samplers, the ground samplers did not collect sufficient samples for a definitive analysis. Crude/residue analyses showed the burn resulted in a significant reduction of PAH in the original oil, most of the reduction was thought to be simply evaporation or destruction from combustion. The residue did not have the degree of enrichment of the higher-molecular-weight PAHs as was the case in bench-scale burn experiments.

VOC, C_2 - C_{12} VOC and dioxin/furan measurement likewise did not show high levels of contamination from the burn itself for the same reason mentioned above. Most of the elevated levels of contaminants could probably be due to evaporation of the oil itself. Insufficient sampling was conducted to investigate the background levels from the weathering process.

A novel means of sampling using a RC helicopter was tried out. Although not typical of the scenario the helicopter was envisaged to perform, the exercise was deemed successful and valuable field experience was obtained.

Acknowledgements:

The authors are indebted to J. Boucher (Agriculture Canada) for his ICP analysis and Dr. Cao (Emergencies Science Division, RRETIC) for the QA study on ICP.

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FIGURE 2

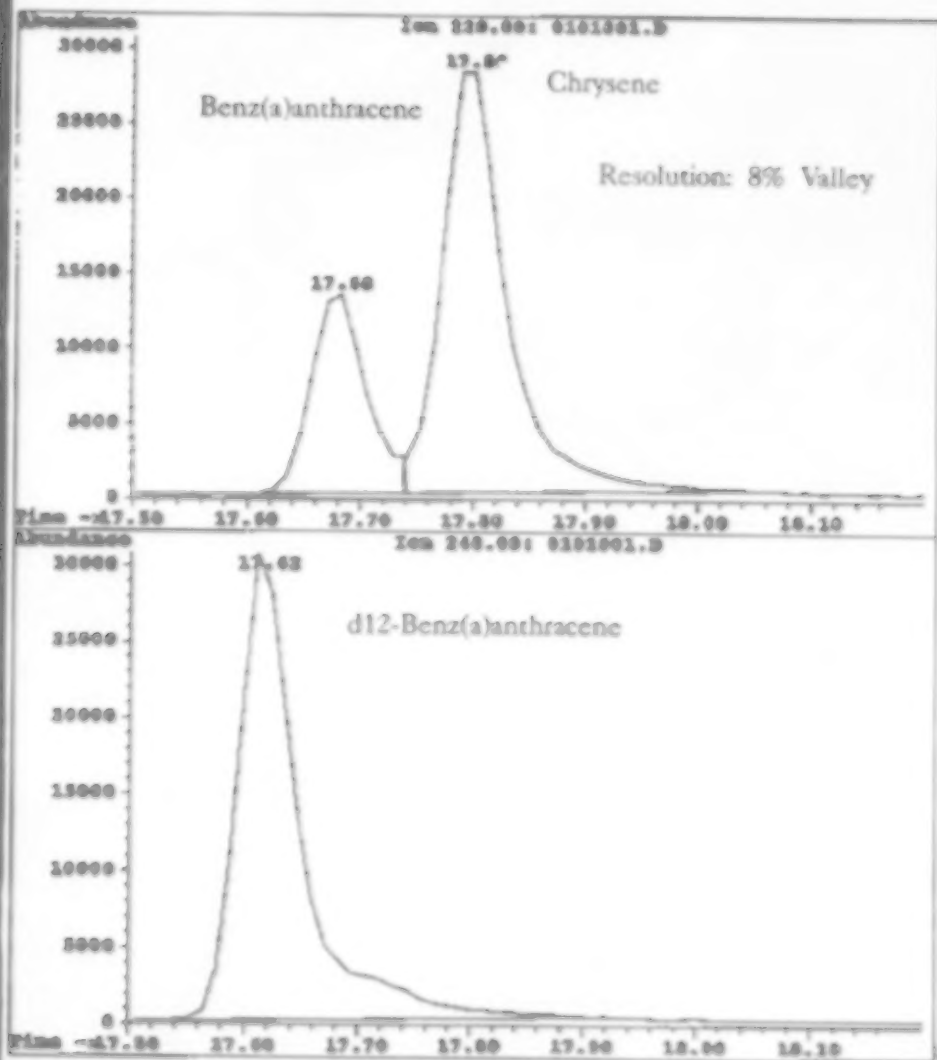


FIGURE 3

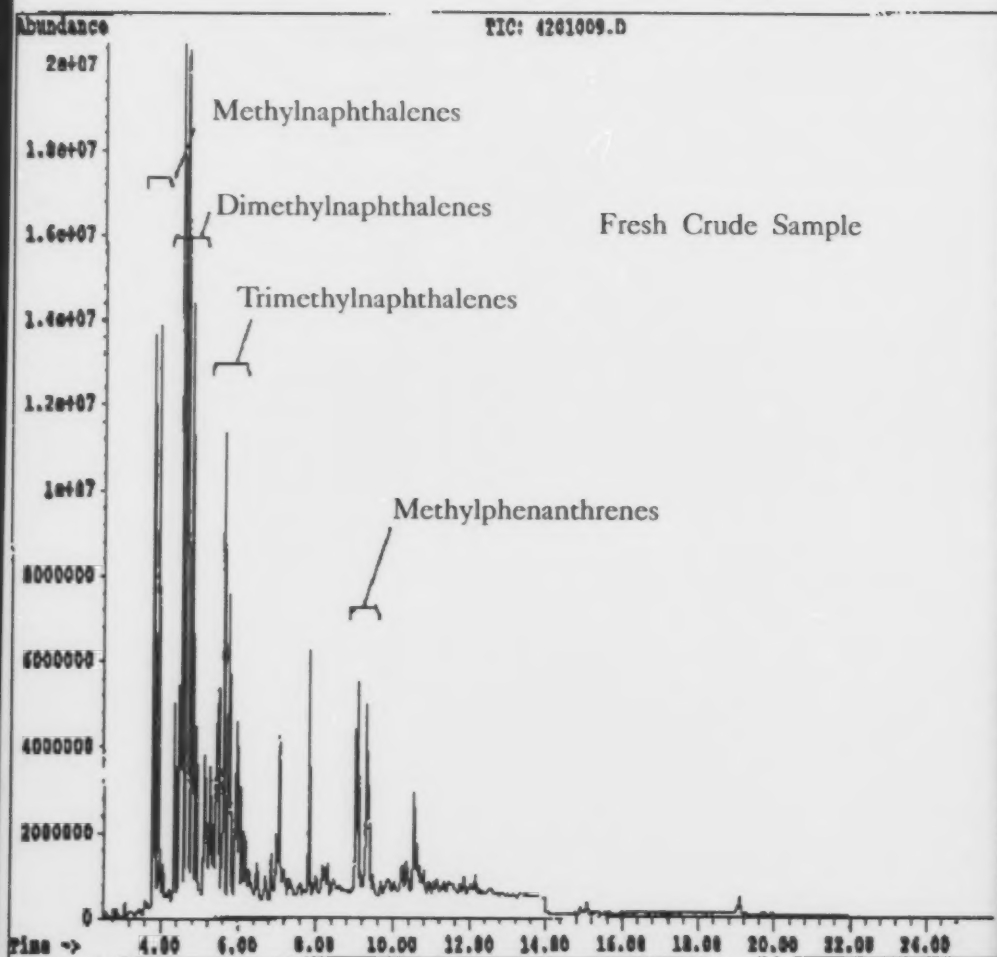
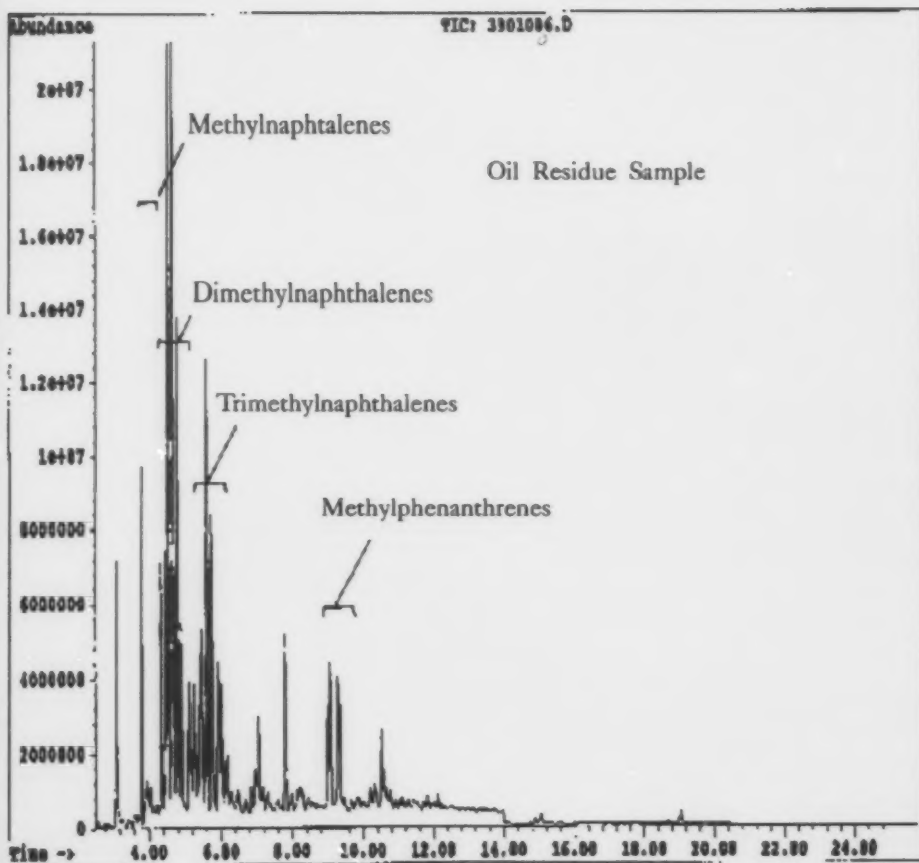


FIGURE 4



Air Sampling And Monitoring at
the Kuwait Oil Well Fires

by

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In response to the more than 500 oil well fires in Kuwait, the Saudi Government requested U.S. technical assistance on the public health and environmental impact of the fires. The U.S. Embassy in Saudi Arabia concurred in this request, and voiced its additional concern about the health effects of the fires on troops in the region, as well as thousands of American citizens residing in the Gulf countries. Similar concerns were also expressed by the U.S. Embassy in Kuwait and the Kuwait Government. An Interagency Air Assessment Team was formed and deployed to the Persian Gulf Area.

The initial air sampling and monitoring program conducted by the U.S. Interagency Air Assessment Team in Kuwait and Saudi Arabia had the following objectives:

1. Determine if there was an acute health threat associated with the Hydrogen Sulfide (H₂S) and Sulfur Dioxide (SO₂) gases being emitted from the burning oil wells.

This objective was accomplished by collecting Real Time Measurements (i.e., instantaneous readings) using portable instruments for the following parameters: H₂S, SO₂, oxygen, and total particulate. These measurements were collected at 13 locations in Kuwait and Saudi Arabia, U.S. Embassies in Kuwait and Riyadh, MEPA Dhahran, at five oil well fields, and at various locations near the oil fields in Kuwait. The results from the March 13-20 monitoring are summarized in Table 2.

The highest readings were recorded from measurements taken in the smoke plumes in the oil fields. The results from this monitoring did not indicate an acute health threat. However, if conditions change (i.e., fires are extinguished without capping, allowing high levels of gases), an acute threat near the wells may occur.

The highest levels observed were: particulate - 5.4 mg/m³, VOCs - 2.5 ppm (adjacent to large pools of oil), H₂S

- 42 ppb, and SO₂ - 2 ppm. It should be noted that the detection limit for the SO₂ monitor is 1-2 ppm. A different SO₂ monitor with a detection limit of 0.1 ppm did not indicate SO₂. Also, the field personnel were unable to detect any sulfur odors at any of the locations. Therefore, the SO₂ levels of 1-2 ppm should be used with caution.

The only elevated levels observed in the monitoring conducted in the population areas were for particulates. A reading of 480 ug/m³ was obtained at MEPA in Dhahran, Saudi Arabia. Based on field observation, this reading was probably a combination of smoke from the fires and sand. Baseline particulate levels, due to blowing sand in Saudi Arabia and Kuwait, range from 200-3000 ug/m³.

Further sampling and monitoring occurred from 3/24 - 3/27. These results are also attached. The results from this monitoring are similar to the previous monitoring results. In general, the particulate concentrations at ground level in the oil fields were lower than in the downwind areas outside the fields, except when in the direct path of a ground level plume. The downwind locations most heavily affected vary, depending on wind speed, temperature, humidity, and other diurnal factors.

The real time particulate readings during this phase are 15 and 20 minute averages. The highest reading occurred at the Ahmadi Hospital, with a 20 minute average reading of 0.935 mg/m³ with a single highest reading of 1.16 mg/m³. Other successive 20 minute averages taken at this location display the variation in particulate levels at the same location, as conditions such as wind direction change.

2. The second objective was to identify and quantify the gaseous and particulate by-products that are associated with the burning oil wells.

This objective has partially been accomplished. Samples from 10 locations have been analyzed by the Environmental Response Team (ERT) laboratory in the U.S. The air samples were collected for the following parameters at all locations: volatile organics (VOCs); polycyclic aromatic hydrocarbons (PAHs) such as naphthalene, benzo[a]pyrene; heavy metals; SO₂; and inorganic acids (i.e., sulfuric, nitric, etc.). A limited number of samples were collected for H₂S, formaldehyde, CO, and total nuisance dust. For specific findings relevant to these samples, see the Section entitled, "Air Sampling Results."

3. The third objective was to determine if the materials associated with the fires were affecting areas where American citizens were located.

This objective will partially be accomplished by reviewing the data from the samples taken at MEPA Dhahran,

Saudi Arabia, U.S. Embassies in Kuwait and Riyadh, Camp Freedom Kuwait, and Port Shuaybah, Kuwait; and reviewing the air monitoring data being collected by MEPA and ARAMCO in Saudi Arabia air monitoring stations and sulfur dioxide data taken at temporary hospital locations in Kuwait City.

In order to complete this objective in a sound scientific manner, sampling for PM₁₀ particulate (i.e., particulate less than 10 microns in size), which are the respirable particulate, and samples from the plume above ground level were taken at a later date. Also, the air monitoring network proposed by the U.S. Interagency Air Assessment Team was implemented.

AIR SAMPLING RESULTS:

The results from the air samples collected for sulfur dioxide, volatile organics, and inorganic acids from 3/13 - 3/20 in Kuwait and Saudi Arabia confirmed the real time measurements and sampling and analysis performed by the Kuwaitis and the Saudis. These results confirmed the conclusion of the U.S. Interagency Air Assessment Team that the primary hazards from the oil well fire is with the particulate matter.

The highest level of sulfur dioxide (0.68 ppm) was detected in the smoke plume of the Burgan Oil Field. This level is above the EPA 24 hour (0.14 ppm) and 3 hour (0.5 ppm) limit. None of the sulfur dioxide samples collected in populated areas exceeded the EPA air quality limits.

The organic vapor analysis showed that compounds associated with petroleum (i.e., benzene, toluene, and aliphatic hydrocarbons such as n-heptane (n-C7)) were detected. The highest levels (i.e., 10-20 ppb level) were detected in the smoke plume in the oil fields and a grab (SUMMA) sample collected at ground level near a pool of oil in the Sabiriyah well field. The inorganic acid analysis showed low ppb levels for both sulfuric and nitric acid. Based on this limited data, the sulfur dioxide and nitrous oxide that may be by-products from the burning of the oil are not being formed in large amounts.

The results from the particulate analysis for polycyclic aromatic hydrocarbons (PAHs) and heavy metals showed very low levels of both parameters in the samples collected in the populated areas and in the oil fields. The only metals detected were those associated with materials found in the sand particles (i.e., sodium, aluminum, magnesium, etc.).

Based on these limited number of samples, the major hazard associated with the oil well fires seems to be the particulate matter being emitted. The monitoring and sampling program discussed in the Air Monitoring Strategy

Plan should help further define the hazards associated with the particulates.

The complete results from the sampling are summarized in the attached exhibits. Only the compounds detected are listed.

PARAMETERS:

The air samples collected at the oil well fields, Camp Freedom, MEPA Dhahran, Saudi Arabia, and U.S. Embassies in Kuwait and Riyadh, Saudi Arabia were analyzed for the following parameters:

PAHs:

Naphthalene, 2-Methylnaphthalene, 1-Methylnaphthalene, Biphenyl, 2,6-Dimethylnaphthalene, Acenaphthylene, Acenaphthene, Dibenzofuran, Fluorene, Phenanthrene, Anthracene, Carbazole, Fluoranthene, Pyrene, Benzo[a]anthracene, Chrysene, Benzo[b]fluoranthene, Benzo[k]fluoranthene, Benzo[e]pyrene, Benzo[a]pyrene, Indeno(1,2,3-cd)pyrene, Dibenzo[a,h]anthracene, Benzo[g,h,i]perylene.

Inorganic Acids:

Hydrochloric, Phosphoric, Sulfuric, Nitric, Hydrofluoric.

Metals:

Platinum, Titanium, Molybdenum, Zirconium, Silver, Aluminum, Beryllium, Cadmium, Calcium, Chromium, Cobalt, Copper, Iron, Magnesium, Manganese, Sodium, Nickel, Lead, Tin, Vanadium, Zinc.

Volatile organics:

1,1,1-Trichloroethane, Cyclohexane, Carbon Tetrachloride, Benzene, Cyclohexene, n-Heptane (n-C7), 1,2-Dichloropropane, Trichloroethane, 1,4-Dioxane, Methylcyclohexane, Methylisobutylketone, Toluene, n-Octane (n-C8), Tetrachloroethane, Chlorobenzene, Ethylbenzene, para-Xylene, Bromoform, Styrene, o-Xylene, n-Nonene, n-Nonane (n-C9), 1,1,2,2-Tetrachloroethane, Cumene, Mesitylene, Alpha-methylstyrene, 1,3-Dichlorobenzene, 1,4-Dichlorobenzene, 1,2-Dichlorobenzene, Benzyl Chloride, alpha-Terpene, D-Limonene, 4-tert-Butyltoluene, 1,2,4-Trichlorobenzene, Naphthalene, 4-Phenylcyclohexene, n-Decane (n-C10), n-Decene, n-Undecene, n-Undecane (n-C11), n-Nonanal, n-Dodecane (n-C12), n-Tridecane (n-C13), n-Tetradecane (n-C14), n-Pentane (n-C15), n-Hexadecane (n-C16).

Others:

Formaldehyde and Sulfur Dioxide.

U.S. EMBASSY, KUWAIT

Results for 3/16

PAHs:
none detected detection limit: 2 - 4.6 ppb

Sulfur Dioxide:
none detected detection limit: 0.04 mg/m3

Inorganic Acids:
none detected detection limit: 1 - 6 ppb

VOCs:
Benzene 0.4 ppb, n-Heptane 0.13 ppb, Toluene 0.61 ppb,
Ethylbenzene 0.1 ppb, para-Xylene 0.29 ppb, o-Xylene
0.12 ppb.

Metals:
Na < 1.0 ug/m3, Mg 2 ug/m3, Fe 2 ug/m3, Ca 8 ug/m3, Al
2 ug/m3.

Results for 3/17

PAHs:
Naphthalene 0.31 ppb

Sulfur Dioxide:
< 0.02 mg/m3

Inorganic Acids:
HCl 3.0 ppb, H2SO4 1.0 ppb, HNO3 2.0 ppb

VOCs:
Cyclohexane 1.31 ppb, Benzene 4.0 ppb, n-Heptane 6.0
ppb, TCE 0.7 ppb, Methylcyclohexane 2.0 ppb, Toluene
7.7 ppb, n-Octane 3.0 ppb, Ethylbenzene 1.7 ppb,
p-Xylene 5.4 ppb, Styrene 0.4 ppb, o-Xylene 2.4 ppb,
n-Nonane 1.9 ppb, Cumene 0.2 ppb, Mesitylene 0.6 ppb,
D-Limonene 0.1 ppb, n-Decane 1.5 ppb, n-Undecane 1.0
ppb, n-C12 0.7 ppb, n-C13 0.4 ppb.

Metals:
Na 10 ug/m3, Mg 2 ug/m3, Fe 3 ug/m3, Ca 10 ug/m3, Al
2 ug/m3.

U.S. EMBASSY, KUWAIT, continued

Results for 3/18

PAHs:

Naphthalene 0.16 ppb

Sulfur Dioxide:

< 0.05 mg/m3

Inorganic Acids:

HCl 6 ppb, HNO3 2 ppb, H2SO4 1.0 ppb.

VOCs:

Cyclohexane 1.2 ppb, Benzene 5.2 ppb, n-C7 8.1 ppb, Methylcyclohexane 3.0 ppb, Toluene 14.6 ppb, n-C8 4.7 ppb, Ethylbenzene 3.2 ppb, p-Xylene 9.3 ppb, o-Xylene 4.7 ppb, n-C9 2.7 ppb, Cumene 0.3 ppb, Mesitylene 1.3 ppb, Naphthalene 0.18 ppb, n-C10 1.7 ppb, n-C11 1.0 ppb, n-C12 0.7 ppb, n-C13 0.3 ppb.

Metals:

Na 5 ug/m3, Mg 1 ug/m3, Fe 1 ug/m3, Ca 7 ug/m3, Al 1 ug/m3.

CAMP FREEDOM

Results For 3/17

PAHs:

Naphthalene 0.09 ppb, 2-Methylnaphthalene 0.06 ppb,
1-Methylnaphthalene 0.04 ppb.

Sulfur Dioxide:

0.12 mg/m³ 0.045 ppm

Inorganic Acids:

HCl 16 ppb, HF 23 ppb, H₂SO₄ 31 ppb

VOCs:

Cyclohexane 7 ppb, Benzene 4.6 ppb, n-C7 25.6 ppb,
Methylcyclohexane 9.5 ppb, Toluene 13 ppb, n-C8 18
ppb, Ethylbenzene 2.7 ppb, p-Xylene 8 ppb, o-Xylene
4.5 ppb, n-C9 10.9 ppb, Cumene 0.5 ppb, Mesitylene 1
ppb, Naphthalene 0.18 ppb, n-C10 6.3 ppb, n-C11 4.1
ppb, n-C12 2.3 ppb, n-C13 0.9 ppb, n-C14 0.5 ppb.
These levels may also include emissions from vehicles
in the area.

Metals:

No Data.

Results for 3/18

PAHs:

Naphthalene 0.28 ppb

Sulfur Dioxide:

<0.04 mg/m³ , < 0.015 ppm

Inorganic Acids:

HNO₃ 4.0 ppb, H₂SO₄ 4 ppb.

VOCs:

Cyclohexane 2.8 ppb, Benzene 6.9 ppb, n-C7 9.7 ppb,
Methylcyclohexane 3.9 ppb, Toluene 16 ppb, n-C8 5.4
ppb, Ethylbenzene 3.1 ppb, p-Xylene 9.5 ppb, Styrene
0.3 ppb, o-Xylene 4.5 ppb, n-C9 3 ppb, Cumene 0.3 ppb,
Mesitylene 1.1 ppb, n-C10 1.5 ppb, n-C11 0.8 ppb,
n-C14 0.2 ppb.

Metals:

Al 2 ug/m³, Ca 8 ug/m³, Fe 2 ug/m³, Mg 2 ug/m³, Na 3
ug/m³.

MEPA DHAHRAN, SAUDI ARABIA

Results For 3/13

PAHs:

none detected

Sulfur Dioxide:

<0.1 mg/m³, <0.037 ppm

Inorganic Acids:

H₂SO₄ 5 ppb.

VOCs:

Benzene 0.3 ppb, Cyclohexane 0.1 ppb, Toluene 0.5 ppb,
Ethylbenzene 0.1 ppb, p-Xylene 0.2 ppb, o-Xylene 0.1
ppb, Mesitylene 0.04 ppb.

Metals:

Al 2 ug/m³, Ca 5 ug/m³, Fe 2 ug/m³, Mg 2 ug/m³, Na 1
ug/m³.Results For 3/14

PAHs:

none detected

Sulfur Dioxide:

<0.08 mg/m³, < 30 ppb.

Inorganic Acids:

HNO₃ 2 ppb, H₂SO₄ 6 ppb.

VOCs:

Cyclohexane 0.2 ppb, Benzene 0.5 ppb, n-C7 0.8 ppb,
Methylcyclohexane 0.3 ppb, Toluene 0.7 ppb, n-C8 0.4
ppb, Ethylbenzene 0.1 ppb, p-Xylene 0.3 ppb, o-Xylene
0.1 ppb, n-C9 0.3 ppb.

Metals:

Al 3 ug/m³, Ca 14 ug/m³, Fe 3 ug/m³, Mg 4 ug/m³, na 8
ug/m³.

U.S. EMBASSY RIYADH, SAUDI ARABIA

Results For 3/28

PAHs:

none detected

Sulfur Dioxide:

< 0.08 mg/m³ , < 30 ppb

Inorganic Acids:

NO₃ 3 ppb, H₂SO₄ < 2 ppb.

VOCs:

Benzene 0.3 ppb, Toluene 0.6 ppb, Ethylbenzene 1.0 ppb, p-Xylene 0.3 ppb.

Metals:

Al 2 ug/m³, Ca 4 ug/m³, Fe 1 ug/m³.

PORT SHUAYBAH

Results For 3/17

PAHs:

no data

Sulfur Dioxide:

< 0.05 mg/m³ , 19 ppb

Inorganic Acids:

H₂SO₄ 19 ppb.

VOCs:

Benzene 4.2 ppb, n-C7 13 ppb, Methylcyclohexane 5.3 ppb, Toluene 15 ppb, n-C8 5.6 ppb, p-Xylene 6.9 ppb, Ethylbenzene 2.2 ppb, o-Xylene 2.9 ppb, n-C9 3.8 ppb, Cumene 0.2 ppb, n-C10 2.9 ppb, n-C11 1.9 ppb, n-C12 1.4 ppb, n-C13 0.8 ppb.

Metals:

Ca 4 ug/m³, Na 7 ug/m³.

A1 MAQUA OIL FIELD

Results for 3/15

PAHs:

no data

Sulfur Dioxide:

<0.3 mg/m³ , <0.1 ppm

Inorganic Acids:

no data

VOCs:

Cyclohexane 0.6 ppb, Benzene 1.8 ppb, n-C7 3.2 ppb,
Methylcyclohexane 1.1 ppb, Toluene 2 ppb,
Ethylbenzene 0.4 ppb, p-Xylene 1.4 ppb, o-Xylene 0.8
ppb, n-C9 2.8 ppb, Mestilylene 0.3 ppb, n-C10 3.3 ppb,
n-C11 3.5 ppb, n-C12 3.3 ppb, n-C13 1.8 ppb, n-C16 1.1
ppb.

Metals:

Al 6 ug/m³, Ca 6 ug/m³, Fe 6 ug/m³.

AL AHMADI OIL FIELD

Results For 3/16

PAHs:

none detected

Sulfur Dioxide:

0.45 mg/m³ , 0.17 ppm

Inorganic Acids:

H₂SO₄ 27 ppb, HNO₃ 10 ppb, HCl 9 ppb.

VOCs:

Cyclohexane 0.4 ppb, Benzene 3.9 ppb, n-C7 2.5 ppb,
Methylcyclohexane 1 ppb, Toluene 2 ppb, n-C8 2.3 ppb,
Ethylbenzene 0.5 ppb, p-Xylene 1.5 ppb, o-Xylene 0.9
ppb, n-C9 2.9 ppb, Mesitylene 0.4 ppb, Naphthalene 0.5
ppb, n-C10 3.4 ppb, n-C11 3.8 ppb, n-C12 4 ppb, n-C13
2.9 ppb, n-C14 2.9 ppb, n-C15 2 ppb, n-C16 1.7 ppb.

Metals:

Al 8 ug/m³, Ca 50 ug/m³, Fe 20 ug/m³.

Formaldehyde:

8 ppb.

SUMMA Data:

SO₂ 0.2 ppm; CO 1.9 ppm

A1 BURGAM OIL FIELD

Results For 3/17

PAHs:

none detected; detection limit 50 ppb

Sulfur Dioxide:

1.8 mg/m³ , 0.8 ppm

Inorganic Acids:

H₂SO₄ 30 ppb, HNO₃ 32 ppb, HCl 15 ppb.

VOCs:

Benzene 8.7 ppb, n-C7 4.6 ppb, Methylcyclohexane 2.5 ppb, Toluene 4.31 ppb, n-C8 5.1 ppb, Ethylbenzene 1.3 ppb, p-Xylene 4.2 ppb, o-Xylene 2.4 ppb, n-C9 7.1 ppb, Naphthalene 1.6 ppb, n-C10 9.1 ppb, n-C11 10.4 ppb, n-C12 11.3 ppb, n-C13 7.8 ppb, n-C14 7.4 ppb, n-C15 5.4 ppb, n-C16 4.6 ppb.

Metals:

Al 20 ug/m³, Ca 120 ug/m³, Fe 20 ug/m³, Mg 30 ug/m³.

Formaldehyde:

20 ppb;

SUMMA Data:

SO₂ 0.23 ppm, CO 1.6 ppm, H₂S none detected (0.1 ppm detection limit.)

A1 WAFRA OIL FIELD

Results for 3/19

PAHs:

no data

Sulfur Dioxide:

none detected 0.3 mg/m3 , 0.11 ppm.

Inorganic Acids:

none detected 10 ppb detection limit

VOCs:

Benzene 2.3 ppb, n-C7 0.6 ppb, Methylcyclohexane 1.6
ppb, Ethylbenzene 0.3 ppb, o-Xylene 0.4 ppb,
Mesitylene 0.4 ppb

Metals:

no data

Hydrogen Sulfide:

awaiting results.

SABIRIYAH OIL FIELD

Results For 3/17

SUMMA DATA:

Ground Level Sample:

H2S none detected (0.1 ppm); SO2 0.13 ppm; CO 1.1 ppm;
NO and NO2 none detected

VOCs:

Benzene 9.8 ppb, Toluene 8.7 ppb, Ethylbenzene 10 ppb,
m&p-Xylene 27.8 ppb o-Xylene 24 ppb, m-Ethyltoluene
15.8 ppb, n-C6 83 ppb, n-C7 60 ppb, n-C8 91 ppb, n-C9
91 ppb, n-C10 89 ppb, n-C11 65 ppb.

3000 ft Sample:

H2S none detected; SO2 0.08 ppm, CO none detected; NO
and NO2 none detected 0.5 ppm.

1000 ft Sample:

H2S, SO2, CO, NO, and NO2 none detected.

Table 1
Kuwait Oil Well Fires Real Time Monitoring
March 13-20, 1991

Site, Date, Time	Total Particulate mg/m ³	Sulfur Dioxide ppm	Hydrogen Sulfide ppm	Volatile Organics ppm
1) MEPA Facility, Dhahran, SA 3/13 1100 hrs	.170	0.0	0.0	0.0
MEPA Facility 3/14 1300 hrs	.480	0.0	0.0	0.0
2) Al Dhuba 3/15 1430 hrs	.420	0.0	0.0	0.0
3) Umm Al Halman 3/15 1500 hrs	.320	0.0	0.0	0.0
4) Mina Abdulla 3/15 1530 hrs	.250	0.0	0.01	0.6
5) Near Al Maqwa Oil Field 3/15 1630 hrs	.010	0.0	0.024	0.8
6) In Al Maqwa Well Plume 3/15 1700 hrs	5.4	0.0	0.006	0.8
7) U.S. Embassy 3/06 0900 hrs	.01	0.0	0.001	0.0
U.S. Embassy 3/18 1230 hrs	.055	1.0	0.005	0.2
8) In Al Ahmadi Well Plume 3/16 1230 hrs	—	0.0	0.032	0.0
In Al Ahmadi Oil Field 3/16 1300 hrs	.120	1.0	0.009	0.0
9) In Al Burgan Well Plume 3/17 1100 hrs	—	1.0	0.015	0.0
10) In Sabiriyah Well Plume, Pooled Oil 3/18 1530 hrs	—	1.0	0.042	2.5
11) In Al Wafra Well Plume 3/19 1200 hrs	.050	2.0	0.015	0.0
12) Freedom City	—	—	—	—
13) U.S. Embassy Riyadh, SA 3/20 1300 hrs	.032	0.0	0.0	0.0

Table 2
Kuwait Oil Well Fires Real Time Monitoring
March 24-27, 1991

Site, Date, Time	Total Particulate mg/m ³	Sulfur Dioxide ppm	Hydrogen Sulfide ppm	Volatile Organics ppm
1) Al Safer Motorway and Wafra Road 3/24 1440 hrs	.825 (15 min. avg.)	2.0	0.0	0.3
2) Al Ahmadi Gathering Center #22 3/24 1530 hrs	.359 (15 min. avg.)	0.0	0.0	0.0
3) Al Ahmadi Hospital 3/24 1530 hrs	.222 (32 min. avg.)	0.0	0.0	0.0
4) 1 mi. NW of Station 2 in Ahmadi Oil Field 3/24 1730 hrs	.256 (10 min. avg.)	0.0	0.0	0.0
5) Al Maga Oil Field, .5 mi south of 7th Ring Road near oil pool 3/25 1400 hrs	.034 (17 min. avg.)	1.0	0.0	0.6
6) Al Ahmadi Oil field (same as Station 4) 3/25 1500 hrs	.561 (13 min. avg.)	0.0	0.003	0.6
7) Al Ahmadi Hospital (same as Station 3) 3/25 1545 hrs	.295 (15 min. avg.)	0.0	0.0	0.0
8) Al Safer and Wafra Road 3/25 1615 hrs	.065 (16 min. avg.)	0.0	0.002	0.0
9) Al Ahmadi Hospital (same as Station 3 and 7) 3/27 1020 hrs	.935 (20 min. avg.)	0.0	0.0	0.2
10) Al Ahmadi Hospital (same as Stations 3, 7, and 9) 3/27 1040 hrs	.457 (20 min. avg.)	—	—	—
11) Al Ahmadi Hospital (same as Stations 3, 7, 9, and 10) 3/27 1100 hrs	.457 (20 min. avg.)	—	—	—
12) Shualba Port 3/27 1215 hrs	.468 (15 min. avg.)	0.0	0.0	0.0

13) Al Safer Motorway and Wafra Road 3/27 1300 hrs	.119 (12 min. avg.)	0.0	0.0	0.0
14) 16 Kilo-meters SE of Al Safer and Wafra Roads 3/27 1330 hrs	.257 (12 min. avg.)	0.0	0.0	0.0
15) 27 Kilo-meters SE of Al Safer and Wafra Roads 3/27 1350 hrs	.227 (15 min. avg.)	—	—	—
16) 5 Kilometers South of Khafji, Saudi Arabia 3/27 1510 hrs	.072 (14 min. avg.)	—	—	—

Table 3
Sulfur Dioxide Bubbler Measurements
(Acidimetric Method)
Temporary Hospital Locations in Kuwait City
March 13-24

Hospital	Date	Concentration ($\mu\text{g}/\text{m}^3$)
Adan	3/14/91	40.31
	3/17/91	43.88
	3/18/91	39.34
	3/19/91	26.18
	3/20/91	27.68
	3/23/91	28.16
	3/24/91	15.99
Mubarek Al Kabeer	3/13/91	193.66
	3/18/91	56.48
	3/19/91	58.11
	3/20/91	42.34
	3/23/91	43.43
	3/24/91	23.72
Al Farwaniya	3/13/91	81.32
	3/16/91	19.21
	3/17/91	29.56
	3/18/91	134.81
	3/19/91	218.65
	3/20/91	27.57
	3/23/91	26.66
	3/24/91	10.54
Al Jahra	3/16/91	32.03
	3/18/91	66.59
	3/19/91	32.54
	3/23/91	13.92
	3/24/91	9.90

In-Situ Burning of Oil Spills: Mesoscale Experiments

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ABSTRACT

In 1991 a series of 14 mesoscale fire experiments were performed to measure the burning characteristics of crude oil on salt water. These oil burns in a pan ranged in size from 6 m square to 15 m square. Results of the measurements for burning rate and smoke emissions are compared to those from previous smaller scale burns conducted both in the U.S. and in Japan. The burning rate as indicated by the regression rate of the oil surface was found to be 0.055 ± 0.01 mm/s for pan fires with effective diameters greater than 7 m. Smoke particulate yields from fires greater than 2 m in diameter were found to be approximately 0.13 of the oil burned on a mass basis. Predictions of smoke plume trajectory and particulate deposition at ground level from the Large Eddy Simulation (LES) model developed as part of this research effort were found to be different from those predicted by the EPA approved SCREEN model. LES is a steady-state three-dimensional calculation of smoke plume trajectory and smoke particulate deposition based on a mixed finite difference and Lagrangian particle tracking method.

INTRODUCTION

In-situ burning of spilled oil has distinct advantages over other countermeasures. It offers the potential to convert rapidly large quantities of oil into its primary combustion products, carbon dioxide and water, with a small percentage of other unburned and residue byproducts. Burning of spilled oil from the water surface reduces the chances of shoreline contamination and damage to biota by removing the oil from the water surface before it spreads and moves. In-situ burning requires

minimal equipment and less labor than other techniques. It can be applied in areas where many other methods cannot due to lack of response infrastructure and/or lack of alternatives. Oil spills amongst ice and on ice are examples of situations where practical alternatives to burning are very limited. Because the oil is converted to gaseous products of combustion by burning, the need for physical collection, storage, and transport of recovered fluids is reduced to the few percent of the original spill volume that remains as residue after burning.

Burning oil spills produces a visible smoke plume containing smoke particulate and other products of combustion which may persist for many kilometers from the burn. This fact gives rise to public health concerns, related to the chemical content of the smoke plume and the downwind deposition of particulate, which need to be answered. Air quality is also affected by evaporation of large oil spills that are not burned. Volatile organic compounds (VOC) including benzene, toluene, and xylene and polycyclic aromatic hydrocarbons (PAH) are found in the air downwind of an evaporating crude oil spill. Laboratory measurements are useful to determine the types of chemical compounds that are expected from large oil spill burns or the evaporation of the spill. To determine the rate of emissions and the transport of the chemical compounds from a burning or evaporating spill, mesoscale experiments have been conducted outdoors using a 15 m square pan. In these experiments a layer of crude oil was discharged onto the surface of a salt water pool. The local air quality during evaporation and burning of the oil was measured.

BACKGROUND

Extensive experimental studies to quantify the capabilities of in-situ burning began in 1983 at the Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) facility in Leonardo, New Jersey under joint funding from the Minerals Management Service (MMS), U.S. Coast Guard (USCG), Environmental Protection Agency (EPA), and Environment Canada (EC). The primary feature of the facility was a water-filled concrete tank 203 m x 20 m x 2.4 m water depth. The tank and associated measurement and control equipment were used to evaluate the performance of oil spill response methods. In the studies conducted at OHMSETT, Prudhoe Bay, Amuligak, and several other crude oils were burned to evaluate the effects of selected physical variables including slick thickness, weathering, sea state, wind velocities, air and water temperatures, degrees of emulsification, and degrees of ice coverage on oil removal efficiency [1]. Results showed that 50 to 95 percent of all of the oils tested could be removed from the water surface by burning, as long as emulsification of the oil with water had not occurred before ignition. Ice coverage from less than 30 to 98 percent, wind speeds from calm to 26 m/s (measured 10 m above the water surface), and water temperatures from -1° to 13°C had little effect on the amount of oil removed from the water surface. Weathered, but not emulsified, oils burned with a greater percentage of removal than did the fresh oils. This was unexpected, but appeared to be a function of increased viscosity of the weathered oil [2]. These tank experiments added to the successes in removing large quantities of oil by burning in field experiments conducted by Brown and Goodman [3] and Buist and Twardus [4].

Based upon the success of these research efforts, a joint MMS and EC in-situ burning research program continued in 1985. This research program was designed to study how burning large oil spills would affect air quality by quantifying the products of combustion and developing methods to predict the downwind smoke particulate deposition. Initially, laboratory experiments were conducted by the Center for Fire Research, now the Building and Fire Research Laboratory, at the National Institute of Standards and Technology (NIST). This work sought to quantify the processes involved in oil spill combustion on open waters and in water filled channels formed in broken ice and included measurements of smoke production and prediction of smoke dispersal. Technical support from EC allowed the study to be broadened to include chemical analysis of the oil, oil residue, and oil smoke.

In the first year of the study [5] the burning process was studied at two pool diameters, 0.6 m and 1.2 m. The emission rate, size distribution, and specific extinction coefficient (relative blackness) were measured for the smoke produced by the fires. The structure of the smoke agglomerates was examined by electron microscopy. The burn residue left on the water by natural quenching of the combustion was analyzed and found to be depleted of short chain alkanes and cycloalkanes when compared with the fresh crude oil. A calculation of the induced air flow into a distribution of pool fires simulating the simultaneous burning of oil in many separate ice leads was performed to demonstrate the magnitude of the fire induced wind.

In the second year [6] extensive measurements of the PAH content of the crude oil and the smoke were performed in cooperation with Environment Canada. Measurements showed that about 10 percent of the crude oil was converted to smoke in the combustion process. A methodology was developed with which the downwind dispersal of smoke generated by one or more oil spill fires in close proximity may be predicted.

In the third year [7] smoke emission was measured during the burning of oil layers thin enough to cause boiling in the supporting water layer. Under these conditions both smoke emission and the PAH content of the smoke were reduced compared to burning of thicker layers. The smoke yield was found to decrease by more than a factor of two when the initial oil layer thickness was decreased from 10 mm to 2 mm. Considering 18 different PAH compounds, the total PAH content in the postburn products, oil residue, smoke and vapors, was found to be less than that contained in the oil that was burned. Measurements of the optical properties and sedimentation velocities for aged and diluted smoke samples were performed. The median aerodynamic effective diameter of the smoke particulate size distribution was found to increase by 30 percent after a simulated one day of aging in a smoke plume. These characteristics are important in estimating smoke properties downwind of the oil spill fire. Analyses of smoke dispersal in the atmosphere were continued by formulating a model for smoke particle settling time which is directly related to soot deposition on the ground remote from the combustion site.

In the fourth year [8] measurements focussed on the determination of the agglomeration rate for smoke particles at both ambient temperature conditions, which corresponds to the cooler, diluted smoke in the plume and at a temperature around 100°C, which corresponds to the temperature several flame heights above the fire. Development of the plume dynamics model continued with a formulation in terms of buoyancy induced vortex trajectories (which represent the large scale plume turbulence) so that the agglomeration rate inferred from the laboratory measurements could be incorporated in the plume model. In the laboratory study the agglomerate size was observed to increase with holding time in the aging/dilution collection chamber, while in a steady state plume model, the agglomerate size will increase with downwind position along the plume.

In the fifth year [9] preparations began for the mesoscale burns to be conducted in cooperation with the USCG at their Fire and Safety Test Detachment in Mobile, Alabama. Preparation involved the development of new instrumentation to perform measurements of combustion characteristics and smoke emissions from large crude oil pan fires up to 15 meters in diameter. Many methods of transporting instrument packages into the smoke plume were investigated during the year. Testing indicated that the best method was tethered miniblimps. Efforts in the calculation of smoke plume trajectory were concentrated on developing models capable of predicting the "footprint" of soot particle deposition downwind of a burn.

In the sixth year [10,11,12] measurements were made with the newly developed instrumentation on large oil fires from 3 meters in diameter at the Fire Research Institute in Japan, to 15 meters in diameter (mesoscale) at both the Navy Fire Fighter Training facility in Norfolk, Virginia and the U.S. Coast Guard's Fire and Safety Test Detachment in Mobile, Alabama. Initial two- and three-dimensional calculations of smoke particulate transport were completed.

The effort in the seventh year of the research program was concentrated on analysis of the data from the 1991 mesoscale experiments. The initial results were the major burning characteristics of mass loss rate and fraction of the oil burned that was emitted as particulate. The extensive ground and smoke plume measurements of chemical components emitted from the oil fires remain to be analyzed fully. Additional laboratory measurements of smoke yield were performed with the identical oil used in the mesoscale experiments to examine the effect of scaling. Calculations of the smoke plume trajectory and downwind particulate deposition at ground level were completed.

EXPERIMENTAL FACILITIES

To understand the important features of in-situ burning it is necessary to perform both laboratory and mesoscale experiments. Finally, actual burns of spilled oil at sea will be necessary to evaluate the method at the anticipated scale of actual response operations. In this research program there is a continuing interaction between findings from measurements on small fire experiments performed in the controlled laboratory environments of NIST and the Fire Research Institute (FRI) in Japan, and large fire

experiments at facilities like the USCG Fire Safety and Test Detachment in Mobile, Alabama where outdoor liquid fuel burns in large pans are possible.

At NIST, two major facilities were used to perform measurements on crude oil pool fires ranging in size from 0.085 m to 0.6 m in diameter. The smallest fires, 0.085 m diameter, were conducted in the Cone Calorimeter to determine the effective heat of combustion for the crude oils and evaluate smoke yield using three different measurement methods. The Cone Calorimeter, shown in figure 1, is more formally known as Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter [13]. The name of the apparatus, Cone Calorimeter, is derived from the shape of the heater used to irradiate samples. The heater coils are formed along the inner surface of a truncated cone. By imposing additional thermal radiation on a small sample, the sample is made to burn as if it were in the middle of a larger fire. The major material flammability characteristics can be evaluated using this laboratory apparatus. These include: rate of heat release, effective heat of combustion, total heat release, ignitibility, mass loss rate, smoke specific extinction area, and yields of various gaseous species and particulate.

A larger calorimeter apparatus capable of accommodating samples up to 0.6 m in diameter was used to provide additional NIST laboratory data on the effect of fire diameter on smoke yield from crude oil fires. This instrumented exhaust hood shown in figure 2 has been the workhorse of the laboratory scale studies of crude oil combustion for several years in this research program [5-11]. Samples drawn from the exhaust hood duct were used to quantify the amount of each major combustion product generated per kilogram of crude oil burned, the chemical composition of the smoke including PAH content, the particulate size distribution of both fresh and aged smoke, and the oxygen consumed in the combustion process. Oxygen consumption calorimetry is used to calculate the heat release rate of the fire, which is the primary quantity used to characterize burning intensity. To further characterize the combustion process, additional instrumentation was used to measure radiant heat flux from the flame and the mass loss rate of the burning fuel.

The relatively small, 0.6 m diameter, fires provided a means of measuring fire characteristics under controlled conditions, but are too small to provide an adequate test of measurement equipment being developed for field use. Through the cooperation of the Fire Research Institute (FRI) in Tokyo, Japan, joint studies of crude oil burning characteristics were conducted. FRI maintains a fire test facility in which crude oil pools up to 3 m in diameter are burned, with all of the combustion products collected in a large hood system. Figure 3 shows a 2 m diameter crude oil fire burning in the 24 m x 24 m x 20 m high test hall. This facility could accommodate fires that are large enough so that sampling packages designed for mesoscale tests could be evaluated. The exhaust system for the building was instrumented so that measurements similar to those performed in the NIST facility could be made by effectively using the entire FRI test building as a smoke collection hood.



Figure 1. NIST Cone Calorimeter

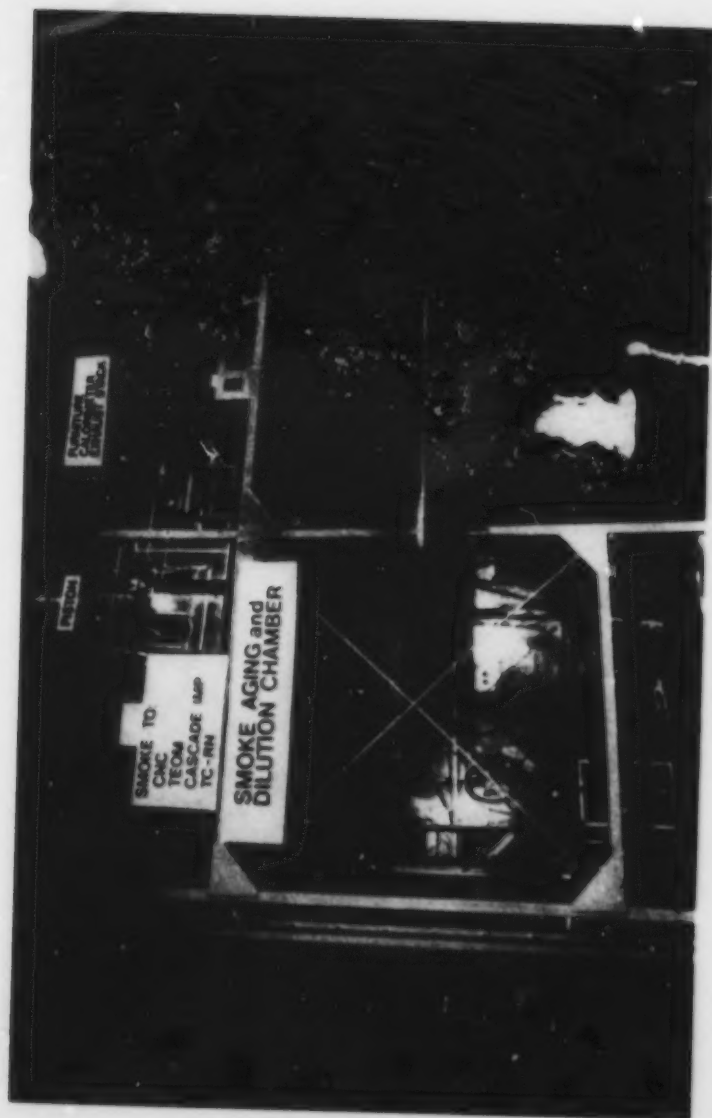


Figure 2. NIST Large Calorimeter



Figure 3. Two meter diameter crude oil fire at FRI

ELEMENTAL ANALYSIS OF CRUDE OILS

Two types of oil were used in this study. A Louisiana crude oil and a Murban crude oil. Samples of each oil type were analyzed for composition by a commercial laboratory. Two separate analyses were performed by the same laboratory for each oil and the average results are presented in table 1.

Table 1. Elemental analysis of Louisiana and Murban crude oils

Element	Louisiana Oil (mass fraction)	Murban Oil (mass fraction)	Repeatability
Carbon	0.862	0.848	$\pm 0.2 \%$
Hydrogen	0.134	0.141	$\pm 1.6 \%$
Sulfur	0.000	0.008	$\pm 4.0 \%$

EFFECTIVE HEAT OF COMBUSTION

Heat is released in all combustion (oxidation) reactions. The amount of heat released per unit quantity of fuel oxidized is defined as the heat of combustion. Heat of combustion is normally determined in an ASTM D 240 oxygen bomb calorimeter, in which a known mass of fuel is burnt completely in an atmosphere of pure oxygen. In fires, however, incomplete combustion occurs resulting in the formation of carbon monoxide, smoke particles, and other incomplete combustion products. The amount of heat actually released from the fire divided by the amount of fuel burned is termed the effective heat of combustion. These two quantities were measured in the Cone Calorimeter, and the effective heat of combustion for each of the two oils used in this study was determined. The effective heat of combustion for the Louisiana oil was 41900 kJ/kg, and 42700 kJ/kg for the Murban oil. This effective heat of combustion is used in conjunction with the mass loss data for the large-scale fires to determine the heat release rate of the large fires.

MESOSCALE CONFIGURATION

The mesoscale burns of crude oil were carried out under the direction of NIST at the United States Coast Guard Fire and Safety Test Detachment facility on Little Sand Island in Mobile Bay Alabama. Little Sand Island is approximately 0.2 km² in size and includes three decommissioned ships docked in a lagoon. The ships and facilities on the island have been used for a wide variety of full-scale marine fire tests. Figure 4 is a photograph of a burn in progress, and figure 5 is a plan view of the portion of the island used for the oil spill burns.

The burns were conducted in a nominal 15 m square steel burn pan constructed specifically for oil spill burning. The burn pan was 0.61 m deep and was constructed

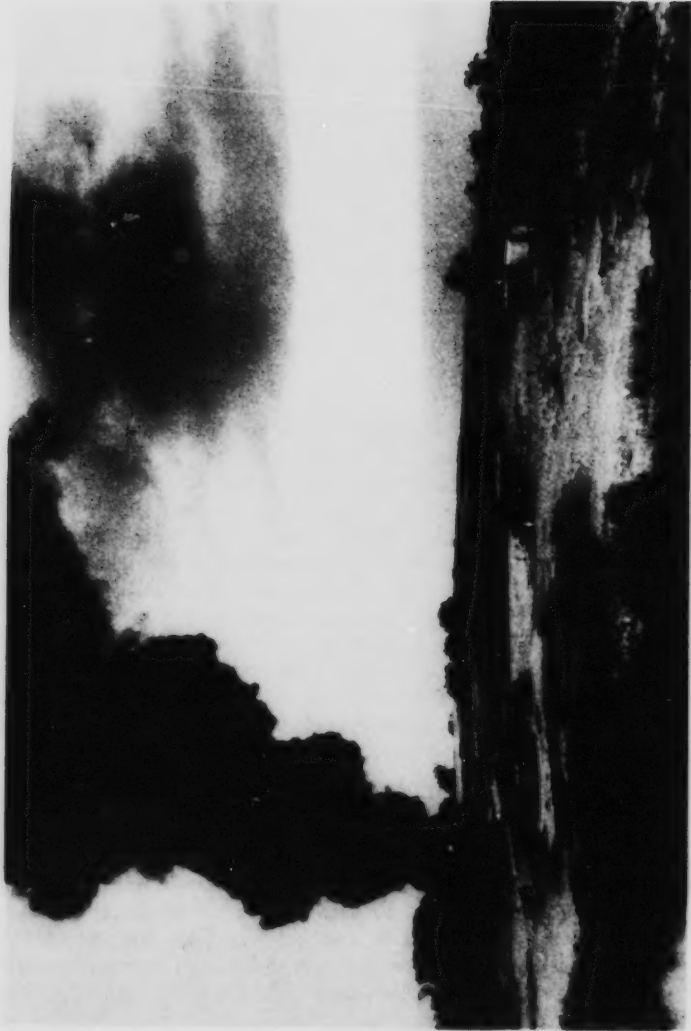


Figure 4. USCG Safety and Fire Test Detachment mesoscale burn facility in Mobile, Alabama

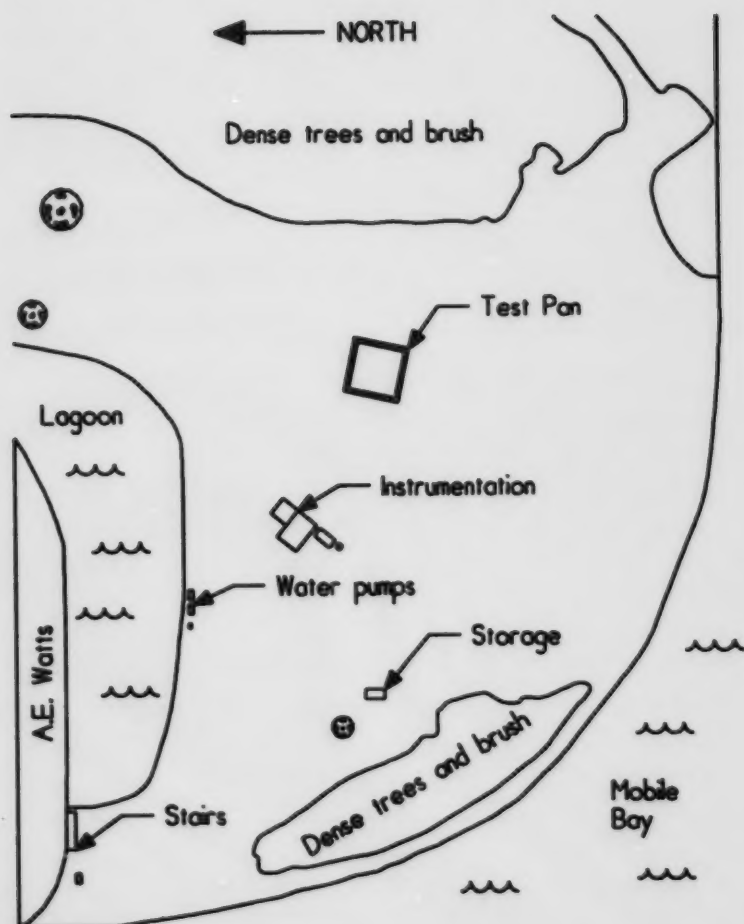


Figure 5. USCG mesoscale burn facility site plan

with two perimeter walls approximately 1.2 m apart forming an inner and outer area of the pan. The inside dimensions of the inner area of the pan were 15.2 m by 15.2 m. The two perimeter walls were connected with baffles and the space between the walls, which formed the outer area of the pan, was filled with bay water during the burns. The base of the pan was 6 mm thick steel plate and the walls were 5 mm thick steel plate. The tops of the walls were reinforced with steel angle to prevent warping during the burns. The base of the pan was located on ground level and was reinforced with steel beams on steel footers under the pan. Water fill pipes were connected to both the inner and outer areas of the pan. Water was pumped directly from Mobile Bay into both the inner and outer areas of the pan. The inner area of the pan was filled with approximately 0.5 m of water and the crude oil was added on top of the water. An oil spill containment dike approximately 0.5 m high was constructed 4 m from the outer edge of the pan.

The crude oil used in the mesoscale burns was obtained from an oil storage facility in Louisiana. The oil originated from wells in the Louisiana area and is thus referred to as Louisiana crude oil. Properties of the oil, as measured by independent oil testing laboratories, are given in table 2.

Table 2. Louisiana crude oil properties

Property	Value (measured by independent laboratories)
Specific Gravity	sample 1 - 0.8453 sample 2 - 0.8448
API Gravity @ 15.6°C (60°F)	sample 1 - 35.9 sample 2 - 36.0
Kinematic Viscosity @ 37.8°C (100°F)	5.49 mm ² /s (5.49 cSt)
Reid Vapor Pressure	26.9 kPa (3.9 lbf/in ²) absolute
Flash Point - Pensky Martin Closed Cup	less than ambient

Crude oil was fed to the burn pan via an underground pipe. A vertical section of the oil fill pipe penetrated the base of the pan and terminated in flanged fitting located below the water level. A plate was bolted on the flanged fitting with spacers between the plate and the flange. This allowed the oil to be injected horizontally below the surface of the water. The supply side of the oil fill pipe terminated approximately 200 m from the burn pan. Gate valves were located in the supply pipe next to the pan, 52 m from the pan and at the supply point. A check valve and a orifice plate flow meter were located in the supply pipe near the pan.

Three different primary burn areas were used in the series. These areas consisted of the full inner pan with an area of 231 m² and partial pan areas of 114 m² and 37.2 m². The partial pan areas were achieved by partitioning a corner of the inner pan with 0.14 m by 0.14 m timbers covered with sheet steel. Plywood skirts 0.3 m deep were attached to the timbers below the water surface to prevent the oil from flowing under the timbers.

A total of 14 mesoscale burns were conducted. These included two preliminary burns which were used to test instrumentation and procedures, 8 burns to examine the effect of burn area, and 4 burns to examine special conditions. Table 3 gives the size and areas for the mesoscale burns. An effective diameter was calculated for each of the rectangular burn areas. The effective diameter is the diameter of circle with the same area as the rectangular burn area used. The special conditions examined included the use of fire resistant boom, the effect of water spray on smoke emissions and the effect of oil aging on burning.

MESOSCALE INSTRUMENTATION

The fixed position instrumentation in and around the burn pan consisted of thermocouples in the pan, thermal heat flux gauges and instrumented steel plates facing the pan, and a manometer to measure the liquid level in the pan. The data from the thermocouples, heat flux gauges and instrumented steel plates are not reported in this paper.

A portable array of 8 - 0.5 mm diameter bare-bead thermocouples 76 mm apart was used to determine the temperature of the water in the inner pan at two locations on opposite sides of the pan before and after the burns. The data from these thermocouples are not presented in this paper.

A vertical manometer calibrated for water was used to measure the equivalent water level in the pan during the burns. Since the oil and the water in the pan have different densities, a correction must be applied to determine the thickness of the oil layer during the burn. A copper tube was connected to the inner pan water fill pipe on the pan side of the shutoff valve. The tube was run underground to the instrumentation building and connected to a liquid manometer. The liquid level in the manometer was videotaped during the pan fill and burn. The equivalent water level in the pan as a function of time was obtained from the videotape record.

Measurements of atmospheric conditions were made with both ground based and airborne weather stations. The ground based station was located approximately 50 m to the west of the burn pan and 3 m above the ground. The station consisted of a thermistor to measure temperature, a propeller on vane anemometer to measure wind direction and speed and a capacitive relative humidity sensor. Atmospheric data from the ground based weather station were recorded every 120 s with a computerized data acquisition system. The airborne weather station was located approximately 50 m from the pan near the ground station and was positioned for each burn to be well away from the fire plume. The airborne weather station consisted of a thermistor to

measure temperature, a cup anemometer to measure wind speed, an electronic compass to measure wind direction, and a pressure transducer to measure barometric pressure. The airborne weather station was connected to a helium filled miniblomp which was tethered approximately 50 m above the ground during the fires. Data from the airborne weather station were transmitted via radio to a ground based computerized data collection system every 20 s.

Table 3. Mesoscale burn size

Burn No.	Burn Size (m)	Burn Area		Effective Burn Diameter		Burn Area/ Full Pan Area (%)	Features
		(m ²)	(ft ²)	(m)	(ft)		
4/16	6.10 × 6.10	37.2	400	6.88	22.6	16	
4/17	6.10 × 6.10	37.2	400	6.88	22.6	16	
5/16	6.10 × 6.10	37.2	400	6.88	22.6	16	
5/17	6.10 × 6.10	37.2	400	6.88	22.6	16	
5/22	10.7 × 10.7	114	1225	12.0	39.4	49	water spray
5/23	11.9 × 15.2	181	1950	15.2	49.9	78	boom attached two ends, free to move
5/24	11.2 × 15.2	170	1830	14.7	48.2	74	boom attached two ends, free to move
5/28	8.53 × 8.53	72.8	784	9.63	31.6	32	boom attached two ends, restricted to square area
5/29	6.10 × 6.10	37.2	400	6.88	22.6	16	oil aging
5/30	10.7 × 10.7	114	1225	12.0	39.4	49	
5/31	15.2 × 15.2	231	2490	17.2	56.4	100	
6/3	10.7 × 10.7	114	1225	12.0	39.4	49	
6/4	10.7 × 10.7	114	1225	12.0	39.4	49	
6/5	15.2 × 15.2	231	2490	17.2	56.4	100	

The ground based measurements consisted of both real time measurements and samples collected for laboratory measurement. The real time measurements made both up- and downwind of the fire included total particulates and carbon dioxide, and sulfur dioxide concentrations. Filter samples were collected both upwind and downwind of the fire and analyzed in the laboratory for PAH and VOC concentra-

tions. Samples of the fresh oil before the burn, oil residue after the burn, and water in the burn pan after the burn were analyzed in the laboratory for PAH concentration. The results of the ground based measurements and laboratory analysis are not presented in this paper.

Airborne samples were collected for both laboratory analysis and analysis on the ground immediately following the burns. The sampling packages were suspended approximately 60 m below a 5.6 m long 2.3 m diameter tethered helium filled miniblimp. The miniblimp was positioned downwind from the fire with the sampling package centered in the smoke plume. The elevation and downwind position of the sampling package varied with each burn as a function of the plume position. Typically, sampling packages remained in the plume for 600 seconds which permitted an adequate sample to be collected and allowed the natural fluctuations in the plume to be averaged. Since the lift capacity of the miniblimp was limited, in general only a single sampling package could be deployed at a time. In some cases, where the burn was of sufficient duration, two packages were deployed sequentially.

The sampling packages consisted of battery powered pumps which drew samples through filters and discharged a portion of the gas into a collection bag. Filter samples were analyzed in the laboratory for PAH and VOC concentrations. Particulate size distribution was measured using a cascade impactor. In addition, smoke particulate was collected on a thermophoretic transmission electron microscope grid (TEM grid) and analyzed using a transmission electron microscope to determine particle shape. Table 4 gives a list of the airborne samples taken during the mesoscale burns. The smoke yield results will be presented in a later section. The other results from the airborne measurements are not presented in this paper.

MESOSCALE BURN PROCEDURE

Prior to conducting a mesoscale burn, the burn size was selected and for partial pan burns the timber partitions were positioned at the appropriate location. Prior to pumping crude oil into the pan, water was pumped into the outer pan so that the water level was nearly to the top of the pan. Water was also pumped into the inner pan so that the water surface level was approximately 110 mm below the top of the pan. The distance from a reference point at the top of the pan to the surface of the water in the inner pan was measured and recorded. The temperature profile of the water in the inner pan was measured at two locations on opposite sides of the pan.

The crude oil was stored on a barge which was brought to the site prior to a burn. Oil was pumped through a flexible hose from the barge through the underground piping system and into the pan. The approximate quantity of oil delivered to the pan was monitored with an in-line flow meter. When the quantity of oil delivered to the pan approached the desired quantity, compressed air was pumped from the barge to purge the flexible hose. The barge was then disconnected from the flexible hose and the barge departed the site. The distance from the surface of the oil to the fixed reference point at the top of the pan was recorded and an oil sample was taken. The fixed position and ground based instrumentation and data recording were started and

the oil was easily ignited with an extended propane torch. Video cameras were used to record the burn.

Table 4. Mesoscale Airborne Samples

Burn No.	Miniblimp		Start Time (s)	Total Time (s)	Range (m)	Altitude (m)
	No.	Samples				
4/16	1.1	PAH, TEM grid	29	425	61	128
	1.2	smoke yield	1165	245	61	128
4/17	1.1	Formaldehyde, charcoal tube	17	529	61	56
	1.2	PAH, TEM grid	641	226	61	56
5/16	1	PAH	48	1273	56	44
5/17	1	smoke yield	215	681	106	100
5/22	1	smoke yield	107	403	83	38
5/23	1	PAH	--:--	617	48	30
5/28	1.1	quartz filter #1	-10	248	87	45
	1.2	quartz filter #2	436	163	87	45
5/29	1	smoke yield	155	692	47	16
5/30	1	impactor, TEM grid	0	1152	87	45
	2.1	quartz filter	28	210	87	45
5/31	2.1	quartz filter	20	429	103	150+
6/3	1	PAH, charcoal tube	32	1515	109	150+
	2	smoke yield	71	722	109	150+
6/4	1.2	PAH, impactor	387	948	109	160
	2	formaldehyde, charcoal tube, passive filter	12	1351	109	160
6/5	1.1	smoke yield, TEM grid	59	915	100	121
	1.2	PAH, charcoal, passive filter	1134	868	100	121
	2	PAH, passive filter	109	1883	100	121

Note: All times from ignition

When the flames were no longer visible, the temperature profile of the water in the inner pan was measured at two locations on opposite sides of the pan. The distance from the surface of the water/oil residue to the fixed reference point at the top of the pan was recorded and a burn residue sample was taken. The residue was collected with absorbent material and placed in drums for disposal. The quantity of residue was estimated from the volume of the drums filled taking into account the absorbent material and water collected. After four of the burns (5/30, 5/31, 6/3, and 6/5), there was a greater quantity of residue than could be readily collected in two or three drums. It is estimated that there was two to three times the quantity of residue found in the earlier burns due to variations in the extinction process. In these cases after the residue had cooled, a small quantity of diesel fuel was poured on the residue and the diesel and burn residue mixture was ignited. This procedure was repeated up to three times until the residue had been reduced to a manageable quantity. The residue was then collected and measured.

The water spray system used in burn 5/22 was designed by Alaska Clean Seas¹ to examine the effect of water spray on smoke production. Twelve nozzles which produced an umbrella like spray pattern were located approximately 1 m above the fuel surface. Bay water was pumped to the nozzles starting 83 seconds after ignition with a nozzle pressure of 34 kPa. At 673 s after ignition the pressure was increased to 69 kPa, at 507 s the valve to the spray system was closed and the spray terminated at 540 s.

For the oil aging burn 5/29 the oil was pumped in the pan at 0812 hours local time and the burn started at 1627 hours local time. The oil remained on the surface of the pan for a total of approximately 29700 s prior to ignition.

MESOSCALE RESULTS

Table 5 gives a summary of the meteorological conditions measured during each of the burns. The values in the table are averages over the time from ignition to extinction. Wind directions are the direction from which the wind originates with 0° being north. Although the measurements were taken at a single ground and single airborne location and there was some variation in the meteorological conditions during the burns, the burns were of relatively short duration and the averages are representative of the actual conditions. Before and after the burns, profiles of the meteorological conditions were made with the airborne weather station up to an elevation of 100 m. The profiles showed the meteorological conditions to be generally uniform above 20 m.

¹ Certain commercial equipment, instruments, materials, or methods are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or methods used are necessarily the best available for the purpose.

Table 5. Mesoscale meteorological conditions

Burn No.	Ground Weather Station					Airborne Weather Station			
	Wind Speed. (m/s)	Wind Dir. (°)	Temp. (°C)	R.H. (%)	B.P. (kPa)	Alt. (m)	Wind Speed (m/s)	Wind Dir. (°)	Temp. (°C)
4/16	1.5	117	25.3	74	101.9	NA	NA	NA	NA
4/17	1.9	150	24.0	73	101.6	NA	NA	NA	NA
5/16	2.1	141	27.0	81	101.4	50	5.3	150	25.2
5/17	1.7	165	26.3	69	101.5	50	3.9	141	25.2
5/22	4.0	57	24.3	87	101.3	NA	NA	NA	NA
5/23	5.0	107	25.3	85	NA	NA	NA	NA	NA
5/24	2.4	134	25.9	89	NA	51	6.0	120	24.3
5/28	1.2	206	27.5	92	101.8	48	4.1	189	25.3
5/29	5.0	189	30.1	72	101.6	41	9.8	196	26.0
5/30	3.9	168	28.7	72	101.5	48	6.2	168	25.6
5/31	0.8	40	27.3	81	101.4	52	1.3	49	24.5
6/3	1.0	61	26.4	74	NA	NA	NA	NA	NA
6/4	2.1	177	30.2	72	NA	NA	NA	NA	NA
6/5	2.1	41	30.3	69	NA	NA	NA	NA	NA

NA - not available

BURNING RATE

The burning of the crude oil was observed to take place in four distinct phases. The four phases were; 1) spreading, 2) steady burning, 3) steady burning with boiling of the water below the oil layer, and 4) transition to extinction. The spreading phase lasted a relatively short period of time as flames spread on the surface from the single ignition point on the upwind side of the pan to cover the entire fuel surface. Once the entire oil surface was covered with flames, the burning continued at a steady rate until the water below the oil surface began to boil. The onset of boiling was characterized by a noticeable increase in sound and bubbles breaking through the oil surface. During boiling the burning rate increased to a steady rate which was greater than the rate prior to boiling. When the fuel was nearly consumed, the fire began a transition to extinction. This was characterized by areas of the oil surface with no visible

difference in elevation provided a direct measurement of the quantity of oil added to the pan. For the partial pan burns, as oil was added to the confined area of the pan the water level in the unconfined area changed since water was free to flow under the timbers or boom used for containment. The hydrostatic head from the water and the oil in the confined area would equal the hydrostatic head from the water in the unconfined area. Equating the hydrostatic heads in the two areas of the pan yields the following expression for the change in the thickness of the oil layer in the confined area of the pan.

$$\Delta h_o = \frac{\Delta h_{o,w}}{1 - \left(\frac{A_T - A_o}{A_T} \right) \Gamma} \quad (1)$$

where:

Δh_o = change in oil layer thickness in the partial pan area (m)

$\Delta h_{o,w}$ = change in the combined oil layer and water thickness in the partial pan area (m)

A_T = total pan area (m²)

A_o = partial pan area (m²)

Γ = the ratio of the specific gravity of the oil to the specific gravity of water

For the manometer readings, the measured equivalent water level was converted to oil depth and smoothed using a running 13 point (200 s) running average. The oil surface regression rate was calculated using a least squares linear fit over the time for both the steady burning and steady burning with water boiling phases. The average surface regression rate over the total steady burning phase was determined using a linear fit from the point at which steady burning began to the point at which the transition to extinction began. The specific mass burning rate (rate of mass loss per unit area) was calculated from the surface regression rate and the density of the oil. The heat release rate was determined by multiplying the mass loss rate by the effective heat of combustion for the crude oil (41.9 MJ/kg).

Table 7 gives the initial volume of oil, the volume of residue collected, the volume of oil consumed by burning and the percentage of the initial volume of oil consumed by burning. In the cases where the residue was burned before cleanup the number and duration of the residue burns is shown. The oil consumed includes the total oil consumed during both the primary and residue burns. When burning oil is confined in a towed boom, the oil residue is maintained at a sufficient thickness to support burning. The percent of oil consumed during the mesoscale burns is therefore representative of the percent which would be expected to be consumed if the oil were in a towed boom.

flames. Frequently, there were oscillations in the burning behavior with increased and decreased burning area and transition to and from boiling. The burning area decreased toward the downwind side of the pan until extinction. A brief chronology of the observed burning behavior for each of the burns is given in table 6.

Table 6. Mesoscale burn chronology

Burn No.	Effective Burn Dia. (m)	Initial Oil Depth (mm)	Time to Full Involvement (s)	Time to Begin Boiling (s)	Time to Begin Extinction (s)	Time to Extinction (s)
4/16	6.88	90	40	663	1588	1673
4/17	6.88	43	20	564	671	812
5/16	6.88	34	30	1008	1186	1270
5/17	6.88	60	13	850	1135	1267
5/22	12.0	32	62	NA	466	855
5/23	15.2	18	104	220	423	700
5/24	14.7	33	85	270	630	1203
5/28	9.63	31	38	387	486	613
5/29	6.88	62	241	761	1186	1455
5/30	12.0	51	42	591	1035	1082
5/31	17.2	49	15	596	950	1068
6/3	12.0	63	27	825	1215	1251
6/4	12.0	61	47	654	769	1200
6/5	17.2	62	32	641	855	2465

Note: All times from ignition

The average burning rate or the rate at which the oil was consumed during burning was estimated from the burn time and the quantity of oil. For the burns where the manometer operated satisfactorily, the average rate, as well as the rates prior to boiling and during boiling were calculated.

For all burns except the preliminary burn 4/16, the quantity of the oil was determined from the difference in the elevation of the water surface before the oil was added to the pan and the elevation of the oil surface in the pan. For the full pan burns the

Table 7. Mesoscale oil volume

Burn No.	Crude		Residue		Consumed		Consumed (%)	Residue burns
	(m ³)	(gal)	(m ³)	(gal)	(m ³)	(gal)		
4/16	3.36 ¹	887	0.23	60	3.13	827	93	
4/17	1.60	423	0.10	25	1.50	398	94	
5/16	1.30	343	0.33	88	0.97	255	75	
5/17	2.25	594	0.17	44	2.08	550	92	
5/22	3.37	969	0.12	32	3.25	937	96	
5/23	3.31	875	0.33	88	2.98	787	90	
5/24	5.56	1470	0.12	30	5.44	1440	98	
5/28	2.25	594	0.16	41	2.09	553	93	
5/29	2.31	610	0.21	55	2.1	555	91	
5/30	5.80	1530	0.07	18	5.73	1510	99	1st - 1318 s 2nd - not recorded
5/31	11.8	3110	0.16	43	11.6	3065	99	1st - 1054 s 2nd - 460 s
6/3	7.22	1910	0.10	26	7.12	1880	99	1st - 769 s 2nd - 304 s 3rd - 401 s
6/4	6.98	1845	0.30	81	6.68	1765	96	
6/5	14.1	3720	0.14	37	14.0	3680	99	456 s

¹ Estimated from flow meter

Note: Residue quantities after residue burns if applicable

Table 8 shows the average burning rate and surface regression rates based on the measurements of the oil surface level in the pan and the observed burn times. Table 9 gives the same information in engineering units. Figure 6 is a graph of the average surface regression rate as a function of the effective burn diameter. From this graph it appears that for the range of diameters used in the mesoscale burns there is no dependency of surface regression rate on burn area. With the exception of the burn with a regression rate of 0.023 mm/s (5/16) and the burn with water spray (5/22) the mean value is 0.055 ± 0.01 mm/s. The rate of 0.023 mm/s is most likely due to measurement error. The mean value for the burning rate per unit area is 0.047 ± 0.01 kg/s/m² (4.9 ± 1 gal/hr/ft²) and for the heat release rate per unit area is 1950 ± 300 kW/m². The scatter in the regression, burning and heat release rates was due in part to the variable nature of the burns. The wind direction and speed contributed to the

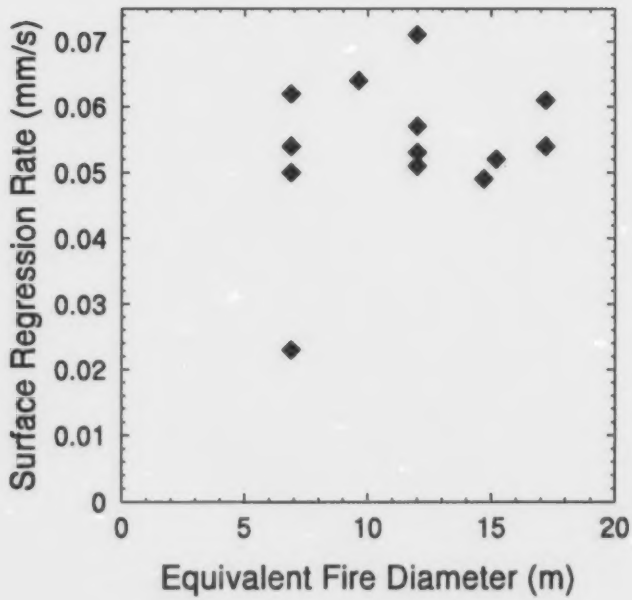


Figure 6. Mesoscale average surface regression rate

wide variation in extinction behavior observed although it did not appear to affect the average burning rate. In some cases there was a rapid transition from full pan involvement to extinction. In other cases the fire would approach extinction with as little as 5% of the fuel surface covered by flames then return to full involvement. In some cases the wind would corral the remaining fuel in a corner of the pan as the fire approached extinction allowing a significant fraction of the oil to be consumed.

Table 8. Mesoscale average burning rate

Burn No.	Effective Burn Dia. (m)	Burn Time (s)	Oil Consumed		Average Burning Rate			Average Surface Regression Rate (mm/s)
			(kg)	(m ³)	(kg/s/m ²)	(kW/m ²)	MW	
4/16	6.88	1548	2645 ¹	3.13	0.046	1925	72	0.054
4/17	6.88	651	1270	1.50	0.052	2195	82	0.062
5/16	6.88	1156	820	0.97	0.019	799	30	0.023
5/17	6.88	1122	1760	2.08	0.042	1765	66	0.050
5/22	12.0	404	2745	3.25	0.060	2500	285	0.071
5/23	15.2	319	2520	2.98	0.044	1825	331	0.052
5/24	14.7	645 ²	4600	5.44	0.042	1755	299	0.049
5/28	9.63	448	1765	2.09	0.054	2270	165	0.064
5/29	6.88	1045 ³	1775	2.10	0.046	1910	71	0.054
5/30	12.0	993	4840 ⁴	5.73	0.043	1790	204	0.051
5/31	17.2	935	9800 ⁴	11.6	0.045	1900	439	0.054
6/3	12.0	1188	6015 ⁴	7.12	0.044	1860	212	0.053
6/4	12.0	1020 ²	5645	6.68	0.049	2030	232	0.057
6/5	17.2	1000 ²	11830 ⁴	14.0	0.051	2145	496	0.061

¹ Estimated from flow meter

² Effective burn time due to long-term intermittent burning at end of the burn

³ Effective burn time due to slow initial fire spread

⁴ Residue was burned

Burn 5/22 which was the burn with water spray showed a slightly higher burning rate than the rest of the burns. When the water spray was initiated it appeared that water reached the surface and the sound was similar to that heard during boiling for the

other burns. It is possible that boiling of the water spray on the fuel surface may have enhanced the burning.

The burning rate from the aged oil was nearly same as the average for the fresh oil. This would indicate that short term aging does not effect burning rate.

Table 9. Mesoscale average burning rate (engineering units)

Burn No.	Effective Burn Dia. (ft)	Burn Time (s)	Oil Consumed (gal)	Initial Oil Thickness (in)	Average Burning Rate (gal/hr/ft ²)	Average Surface Regression Rate (in/min)
4/16	22.6	1548	827 ¹	3.5	4.8	0.13
4/17	22.6	651	398	1.7	5.4	0.15
5/16	22.6	1156	255	1.4	2.0	0.05
5/17	22.6	1122	550	2.4	4.4	0.12
5/22	39.4	404	937	1.3	6.3	0.17
5/23	49.9	319	787	0.7	4.6	0.12
5/24	48.2	645 ²	1440	1.3	4.4	0.12
5/28	31.6	448	553	1.2	5.6	0.15
5/29	22.6	1045 ³	555	2.4	4.8	0.13
5/30	39.4	993	1510 ⁴	2.0	4.5	0.12
5/31	56.4	935	3065 ⁴	1.9	4.7	0.13
6/3	39.4	1188	1885 ⁴	2.5	4.6	0.13
6/4	39.4	1020 ²	1765 ⁴	2.4	5.1	0.13
6/5	56.4	1000 ²	3680 ⁴	2.4	5.3	0.14

¹ Estimated from flow meter

² Effective burn time due to long-term intermittent burning at end of the burn

³ Effective burn time due to slow initial fire spread

⁴ Residue was burned

The burn time used to compute the average burning and surface regression rates was the time from full pan involvement to the beginning of extinction. For burns where an extended period of transition to extinction burning was observed (5/24, 6/4, and 6/5), the effective time of steady burning was adjusted to account for the additional burning during the transition phase. Burn 5/29 exhibited particularly slow initial fire

spread and the steady burn time was adjusted to compensate for the oil consumed during that time period.

After completion of all of the burns, the flow meter in the oil transfer line to the pan was found to have been fouled with a piece of foreign matter. The measurements from the flow meter were not used to calculate the burning rate except for burn 4/16. Complete oil surface level measurements were not available for this burn so the volume of fuel was estimated using the flow meter measurements and a correction based on the flow meter measurement for burn 4/17.

Table 10 gives the oil surface regression rate determined from the measurements of the oil surface level and determined from the manometer. In addition, the surface regression rates before and during boiling as determined from the manometer are given. The regression rates determined from the fuel surface measurements are within 6% of the average rates determined from the manometer. The agreement indicates that the methodology used to determine the regression rates from the surface level measurements and the steady burning duration provides good results within the overall accuracy of field experiments. The observation that the regression rates from the surface level measurements are slightly higher than those from the manometer is an indication that a small amount of the fuel was consumed before and after the steady burning period.

Table 10. Mesoscale average oil surface regression rate

Burn No.	Effective Burn Dia. (m)	Burn Time (s)	Oil Consumed (kg)	Surface Regression Rate			
				From Manometer			From Fuel Level
				Before Boiling (mm/s)	During Boiling (mm/s)	Average (mm/s)	Average (mm/s)
5/31	17.2	935	9800 ²	0.045	0.060	0.051	0.054
6/3	12.0	1188	6015 ²	0.049	0.061	0.053	0.053
6/5	17.2	1000 ¹	11830 ²	0.054	0.073	0.059	0.061

¹ Effective burn time due to long-term intermittent burning at end of the burn

² Residue was burned

Figure 7 shows the average, before boiling and during boiling surface regression rates from the manometer measurements. It can be seen that the burning rate during boiling increased approximately 30% from the burning rate before boiling. This phenomenon has been observed in laboratory experiments and is due to the increased mixing and volatilization of the fuel caused by the boiling of the water under the fuel surface. Also shown in figure 7 are the results from some smaller scale burns which will be discussed in the next section.

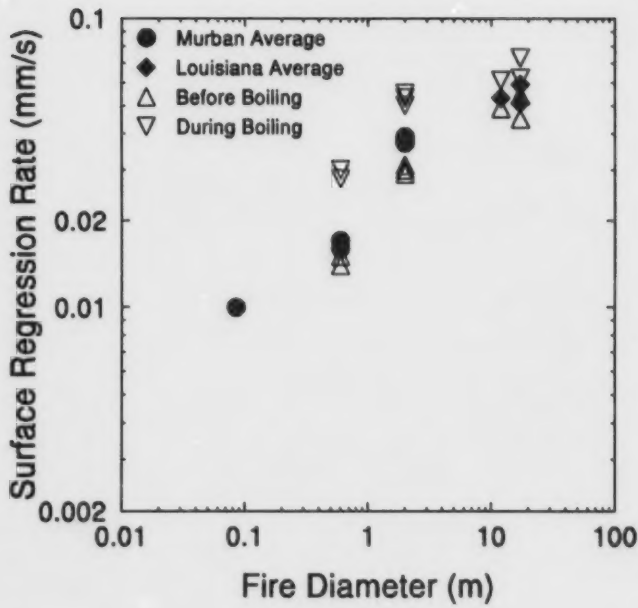


Figure 7. Average surface regression rate (all scales)

BURNING RATE -- EFFECT OF SCALE

Burning rates were measured for pool fires with diameters in the range of 0.085 m to 2 m. These pool fires, after an initial ignition transient, achieved nearly steady burning conditions. Over this range of pool fire diameters, there is a strong increase in burning rate with increasing diameter. This reflects a change from convection-dominated heating of the fuel for the 0.085 m diameter fire to radiation-dominated heating for the larger diameter fires.

Table 11. Laboratory measurements of burning rate for Murban crude oil

		Burning Rate (kg/s/m ²)			Surface Regression Rate (mm/s)		
		Before Boiling	During Boiling	Burn Ave.	Before Boiling	During Boiling	Burn Ave.
Cone Calorimeter D = 0.085 m		NA	NA	0.0082	NA	NA	0.01
Large Calorimeter D = 0.6 m	1	0.017	0.034	0.020	0.014	0.028	0.016
	2	0.018	0.035	0.020	0.015	0.030	0.016
	3	0.018	0.035	0.021	0.015	0.030	0.017
FRI, Japan D = 2.0 m	1	0.037	0.066	0.044	0.031	0.055	0.037
	2	0.035	0.060	0.045	0.030	0.050	0.038
	3	0.035	0.063	0.047	0.029	0.053	0.039

NA - not available, fire extinguished prior to boiling

The study of crude oil combustion on water is complicated by two factors. One is that the oil is being burned in a layer floating on water. The other is that crude oil is a blend of many hydrocarbons with a wide range of boiling points the majority of which are at greater temperatures than the boiling point of water. Distillation measurements of the Louisiana crude oil show that 90 percent of the compounds in the oil have boiling points above 100°C. During burning the surface of the crude oil maintains a temperature of around 300°C. As the fuel is consumed, heat transferred through the fuel to the water below can result in boiling of the water. The boiling effect has been observed in laboratory scale as well as field scale burns. Boiling of the water below the fuel agitates the fuel layer with both fuel and water droplets being sprayed into the flame, substantially increasing the burning rate of the fire. Burning rates are thus reported prior to and during the boiling phase.

Burning and surface regression rates for the Murban crude oil are presented in table 11 and heat release rates in table 12. The burning rate was determined from the mass

of fuel consumed, which was recorded as a function of time, and the duration of burning. The initial oil thickness was 10 mm for the 0.085 m diameter burns, 15 mm for the 0.6 m diameter burns and 25 mm for the 2.0 m diameter burns. From the burning rate, the heat release rate of the fire was calculated by multiplying the mass loss rate of the fuel by the effective heat of combustion of the fuel as described above. The burning rate for the 0.085 m fires was 0.0082 kg/s/m², the surface regression rate was 0.01 mm/s and the heat release rate was 350 kW/m². For the accuracy indicated, identical results were obtained in four different burns with Murban oil as well as three burns with Louisiana oil.

Table 12. Laboratory measurements of heat release rate for Murban crude oil

		Heat Release Rate					
		Before Boiling		During Boiling		Burn Average	
		kW/m ²	kW	kW/m ²	kW	kW/m ²	kW
Cone Calorimeter D = 0.085 m		NA	NA	NA	NA	350	2
Large Calorimeter D = 0.6 m	1	615	174	1200	339	697	197
	2	647	183	1260	356	697	197
	3	647	183	1260	356	736	208
FRI, Japan D = 2.0 m	1	1310	4100	2290	7200	1560	4900
	2	1240	3900	2100	6600	1590	5000
	3	1210	3800	2230	7000	1640	5150

NA - not available, fire extinguished prior to boiling

The 0.6 m diameter burns were conducted in the NIST large calorimeter, and the 2.0 m diameter burns in the FRI facility. For the 0.6 m diameter burns the average burning rate over the entire burn was 0.020 kg/s/m², the average surface regression rate was 0.016 mm/s, and the average heat release rate was 710 kW/m². For the 2.0 m diameter burns the average burning rate over the entire burn was 0.045 kg/s/m², the average surface regression rate was 0.038 mm/s, and the average heat release rate was 1600 kW/m².

Figure 7 shows the surface regression rates before boiling, during boiling and the average over the entire burn. It can be seen that the surface regression rate during boiling was double the rate before boiling for the 0.6 m diameter burns and nearly double for the 2.0 m diameter burns. From figure 7 it appears that boiling resulted in a greater increase in regression rate at the smaller scales. This may be a function of the, oil type, initial oil and water thickness, and other parameters in addition to scale.

SMOKE YIELD MEASUREMENTS

The quantity of smoke produced from a fire may be expressed as a smoke yield which is defined as the mass of smoke particulate produced from burning a unit mass of fuel. Techniques now exist to measure smoke yield both in the laboratory and in the field.

Three methods were used to determine smoke yield; 1) the flux method, 2) the carbon balance method, and 3) the light extinction method. These methods are discussed in detail by Mulholland, et. al [14], and summarized below. The flux method for determining smoke yield consists of measuring the mass of smoke particulate, m_s , collected on a filter, the mass loss of the fuel burned, m_f , and the ratio of the mass flow of air through the exhaust stack to the mass flow through the filter sample, ϕ . The smoke yield calculated by the flux method is termed ϵ_1 , and is given by the expression

$$\epsilon_1 = (m_s/m_f) \phi \quad (2)$$

The carbon balance method is based on a partial carbon balance, and is the only smoke yield measurement method that can be used both in the laboratory and in the field because it does not require measurement or knowledge of the total combustion product flow. In this method, smoke yield is expressed as the product of the measured fraction of carbon in the fuel, f_c , and the ratio of the measured carbon in the form of smoke particulate to the total carbon mass in the combustion products (CO_2 , CO , and smoke aerosols), Y_s . Smoke yield by carbon balance method is denoted by ϵ_2 and given by

$$\epsilon_2 = f_c Y_s \quad (3)$$

The application of the carbon balance method to smoke yield measurements assumes that in the portion of the combustion product flow from which samples are drawn, both the smoke particulate and gaseous combustion products have been transported together from the combustion zone and their concentrations have been equally diluted by entrained air.

A smoke yield measurement that is completely independent of particulate collection on filters is the light extinction method. This method is based on determining the mass concentration of smoke particulates in a known flow rate of combustion products by measurement of visible light attenuation over a known path length. In this study smoke attenuation measurements were made with a laser photometer. The design of the instrument is described by Babrauskas and Mulholland in reference [15]. The light source used in the instrument is a helium-neon laser with a low flow rate air purge to avoid deposition of soot on the optics. Detector electronics processed the signal and the output was recorded directly in units of extinction coefficient, k (m^{-1}). Calibration was accomplished with known neutral density filters introduced in the beam.

As part of the laboratory measurements in the NIST large calorimeter, the assumption that both gaseous and particulate combustion products were drawn together with entrained fresh air into the hood exhaust from which samples were drawn was checked during the burning of 0.6 m diameter crude oil fires. Visual observation indicated all of the smoke particulate was collected by the hood. Concentrations of CO_2 , the major gaseous combustion product from crude oil fires were measured along all of the open areas surrounding the hood. These measurements showed that the concentration of CO_2 was not above ambient anywhere on the perimeter of the apparatus. It was concluded that all combustion products from the fires were being drawn into the hood. Samples for analysis were drawn from the exhaust stack sufficiently downstream of the hood inlet to assure uniform mixing.

In the field, smoke was drawn by a battery operated pump through a pre-weighed filter which collected the particulates. The clean gas passed through the pump to a set of micrometer adjusted flow control valves which metered and diverted a portion gas flow to a 5 liter sample collection bag. A radio controlled switch was used to start and stop the pump remotely as the sampling package was carried into and removed from the fire plume [11]. The filter samples were weighed on a precision balance after the burn and the concentrations of CO_2 and CO in the sample collection bag were determined using a gas chromatograph. In the mesoscale burns, the sampling package was suspended below a tethered miniblomp and was manually maneuvered from the ground and held in the smoke plume downwind of the fire. The altitude and range from the fire are given in table 4. The sample collection times were nominally 600 seconds.

Smoke yield measurements for the two crude oils, Murban and Louisiana, using all three measurement methods in laboratory experiments are presented in table 13. From table 13 it can be seen that there is excellent agreement between all three methods in the Cone Calorimeter. The largest variation between the three methods is 6%. This is most likely because the Cone Calorimeter produces a highly controlled and reproducible fire environment. The smoke yield from the Louisiana crude oil is approximately 20% greater than the yield from the Murban crude oil. This may be due in part to the slightly high carbon content in the Louisiana oil as shown in table 1. The largest variation between the three methods was 43% for the 0.6 m diameter fires and 17% for the 2.0 m diameter fires. This reflects the difficulty of reproducing larger scale fires.

Table 13. Laboratory measurements of smoke yield from crude oil fires

		Fuel Type	Flux Method ϵ_1	Carbon Balance Method ϵ_2	Light Extinction Method ϵ_3
Cone Calorimeter D = 0.085 m	1	Murban	0.053	0.053	0.053
	2	Murban	0.052	0.052	0.049
	3	Murban	0.057	0.057	0.054
	4	Murban	0.054	0.056	0.052
	5	Louisiana	0.063	0.067	0.060
	6	Louisiana	0.058	0.062	0.061
	7	Louisiana	0.063	0.068	0.062
Large Calorimeter D = 0.6 m	1	Murban	0.093	0.080	0.067
	2	Murban	0.093	0.077	0.082
	3	Murban	0.090	0.082	0.063
FRI, Japan D = 2.0 m	1	Murban	0.134	0.139	0.149
	2	Murban	0.128	0.137	0.150

Smoke yields from the mesoscale burns are given in table 14 and smoke yields calculated by the carbon balance method for all scale are shown in figure 8. For the mesoscale burns an estimation of the uncertainty of the smoke yield was determined. The uncertainty interval was based on the accuracy of the balance, the chromatograph and the flow measurements. The uncertainty is shown as error bars in figure 8. From figure 8 it can be seen that smoke yield is dependent on scale. The yield is lower for smaller diameter fires and appears to reach a plateau of approximately 0.13 for fires with diameters above 2 m. In small diameter fires the air which is entrained around the fire perimeter more readily mixes with the fuel resulting in more complete combustion and a lower smoke yield.

The smoke yield from burn 5/17 is distinctly lower than the yields from the other burns. An examination of the start time, sample duration, wind speed and burning rate did provide an explanation for the low result. The smoke yield for the burn with water spray was less than the yield from four of the burns but greater than the yield from one of the burns. The results are inconclusive and at best the water spray might have reduced the smoke yield slightly, although there was no noticeable difference in smoke production during the burn. Although the smoke yield from the aged oil was on the high side of the values, a definite conclusion concerning the smoke yield from aged oil cannot be reached.

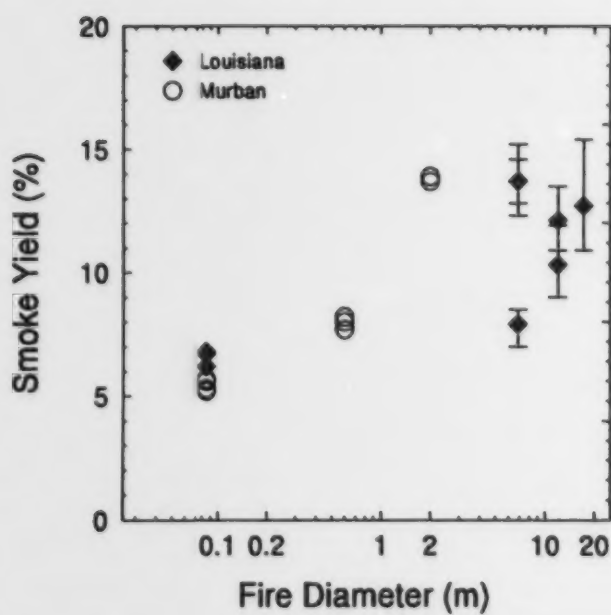


Figure 8. Smoke yield by carbon balance method (all scales)

Table 14. Smoke yield from mesoscale burns

Mesoscale Burn No.	Effective Diameter (m)	Smoke Yield	Uncertainty Interval
4/6/91	6.88	0.137	0.123 - 0.152
5/17/91	6.88	0.079	0.070 - 0.085
5/22/91 Water spray	12.0	0.103	0.090 - 0.119
5/29/91 Aged Oil	6.88	0.137	0.128 - 0.146
6/3/91	12.0	0.121	0.109 - 0.135
6/5/91	17.2	0.127	0.109 - 0.154

PARTICLE SIZE DISTRIBUTION

Particulate size is an important health consideration and also impacts the dynamics of smoke settling. Particulates having an aerodynamic effective diameter less than 10 μm are considered respirable [16] and may be drawn into the lungs with normal breathing. In general small particle sizes have the greatest resistance to settling and can be expected to be carried much further from the burn site than larger particles. In addition to the overall particulate yield from the crude oil fires, it is therefore important to have some knowledge about the particulate size distribution. Smoke particles are an agglomeration of individual spherules. Figure 9 shows a tunneling electron micrograph of smoke particulate emitted from a 1 m diameter crude oil fire. The spherules that make up the structure of the smoke particulate are relatively uniform in size with an average diameter of 0.06 μm . Measurements of smoke particles from 3 m diameter crude oil fires have shown a mixture of spherule diameters in two groupings of 0.15 and 0.06 μm [11].

There is no means to directly translate the observed irregular shape of smoke particles into aerodynamic effective diameters. The aerodynamic effective diameter of a particle is defined as the diameter of a smooth spherical particle with a unit density of 1000 kg/m^3 (1 g/cm^3) that has the same settling velocity in air. Therefore, the aerodynamic effective diameter of a particle depends on the size, shape and density of the particle. Cascade impactors measure particle size distribution by the amount of particulate deposited on a series of plates. The particulate laden air is drawn through the cascade impactor which consists of a series of stages each having a nozzle and plate. Aerodynamic forces determine the size ranges that will be deposited on the plate in each stage and the sizes that will pass through to other stages downstream. The fraction of the total deposition collected by each stage of the device

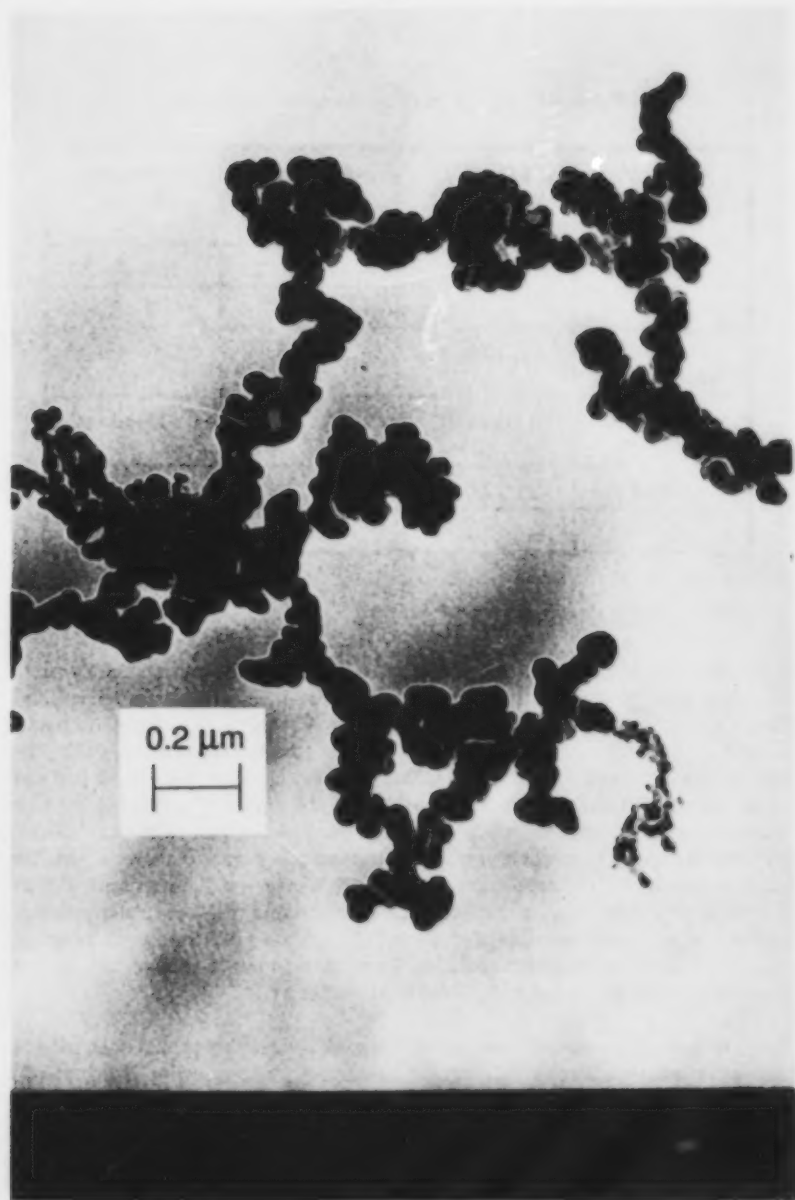


Figure 9. Electron micrograph of a smoke particle from a 1.0 m diameter Murban crude oil fire

determines the distribution of the aerodynamic effective diameter of the particles. The small and light weight commercial impactors used in this study contained six stages. For cases where a small quantity of particulate is expected, some of the stages may be removed. The cutpoint diameter is the aerodynamic effective diameter that is collected with 50 percent efficiency. Ideally the cutpoint diameter represents the largest diameter particle which will not pass to the next stage but in practice some larger particles do move to the next stage. The cut point diameter is a function of the flow rate through the instrument and decreases with increasing flow rate.

In the mesoscale experiments, the impactor was operated at a flow rate of 0.054 L/s with four stages to assure sufficient particulate deposition in each stage. In the laboratory experiments, the impactor was operated at the manufacturers recommended flow rate of 0.033 L/s and all six stages were used. The cutpoint diameters for each stage were determined using the standard correction methods for the instrument [17]. Table 15 shows the cutpoint diameters for each of the stages in the instrument and the back-up filter at the two flow rates used in this study.

Figure 10 shown the cumulative size distribution of smoke particulate from a 2.0 m diameter Murban crude oil fire in the laboratory and a 12.0 m effective diameter Louisiana crude oil mesoscale fire. A comparison of the results from the two fires shows that there is a greater number of smaller particles in the 2.0 m diameter fires than in the 12.0 m diameter fires. For the 2.0 m diameter fires 71% of the particles have an aerodynamic effective diameter of 0.52 μm or less while for the 12.0 m diameter fires 13% have an effective diameter of 0.39 μm or less. For the 2.0 m diameter fires 1% of the particles have an effective diameter of 9.8 μm or greater while for the 12.0 m diameter fires 16 % have a diameter of 7.8 μm or greater.

Table 15. Cascade impactor stage cutpoint size diameters

Flow Rate (L/s)	Stage 1 μm	Stage 2 μm	Stage 3 μm	Stage 4 μm	Stage 5 μm	Stage 6 μm	Back-up Filter μm
0.033	9.8	6.0	3.5	1.55	0.93	0.52	0
0.054	7.8	---	---	1.2	0.70	0.39	0

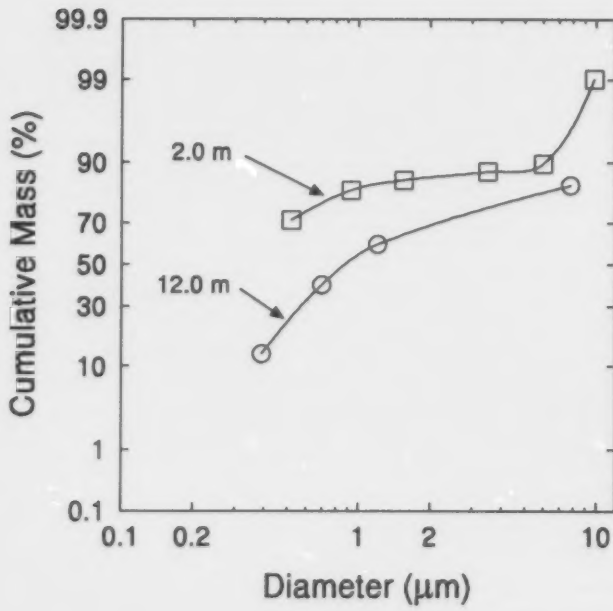


Figure 10. Size distribution of smoke particulate from a 2.0 m diameter Murban crude oil fire and a 12.0 m diameter Louisiana crude oil fire

FIRE PULSATIONS

A natural phenomenon associated with all buoyant diffusion flames is the regular pulsation of the flame caused by interactions with air flow near the base of the flame. For small fires this "flicker" of the flame is well known. Larger laboratory fires also have regular pulsations that generate large scale structures in the smoke plume flow. The frequency of these pulsations (vortex shedding frequency) has been correlated for fire diameters from 0.03 m to 50 m by the equation [18]:

$$f = 1.5 / \sqrt{D} \quad (4)$$

where:

- f = pulsation frequency (Hz)
 D = effective diameter of the fire (m)

This correlation shows there is a strong decrease in the frequency of the pulsations with increasing diameter of the fire. In measurements using a gas burner, Hamins [19] has shown that the pulsation frequency of flames was not sensitive to a factor of two variation in heat release rate with a constant exit velocity of the fuel, although wind is thought to lead to substantial changes in the pulsation frequency [20].

Table 16. Pulsation frequency of pool fires

Burn	Effective Diameter (m)	Wind Speed (m/s)	Frequency Before Boiling (Hz)	Frequency During Boiling (Hz)	Predicted Frequency Eqn. (4) (Hz)
Mesoscale					
5/17	6.88	1.7	0.73±0.08	---	0.57
5/29	6.88	5.0	0.70±0.04	---	0.57
6/3	12.0	1.0	0.42±0.03	0.56±0.07	0.43
6/4	12.0	2.1	0.42±0.07	0.45±0.05	0.43
5/31	17.2	0.8	0.46±0.04	0.44±0.04	0.36
FRI, Japan					
	2.0	---	1.13±0.05	1.29±0.08	1.1

Video recordings of the mesoscale experiments, and 2 m diameter crude oil fires experiments at FRI were analyzed to determine the pulsation frequency of the fire by observing the motion of the flame near the fuel surface. Table 16 lists the measured values of pulsation frequency along with effective fire diameter for the mesoscale experiments and the pan burns at FRI in Japan. For the mesoscale experiments the

near surface wind speed is also listed. For some of the mesoscale fires, a pulsation frequency before and after the onset of boiling was measured. In two of the three experiments in which the burning continued for sufficient time after the onset of boiling to measure the pulsation frequency, no significant increase was found. For the smallest mesoscale experiments (effective diameter of 6.88 m) an increase of almost a factor of three in wind speed did not significantly change the pulsation frequency of the fire. Measurements are generally in agreement with predictions using equation (4) and the data from other fires given in reference [18]. The largest variation, about 1/3 of the predicted frequency, occurred for the 17.2 m effective diameter burn.

SMOKE PLUME TRAJECTORY MEASUREMENTS

Although there are many accidental fires that produce smoke plumes, these opportunities are not useful for gathering data that is needed to validate predictive methods for smoke plume trajectory and particulate deposition. This is because the smoke production and heat release rates of the fire are unknown. The mesoscale pan fire experiments provided a unique opportunity to measure smoke plume trajectories for burns of known particulate emission and fuel burning rates. Measurements of smoke plume trajectories were made in half of the mesoscale burns. The trajectory and radius of the smoke plume were measured using video recordings and subsequently analyzed using digital image processing. Results of these measurements and discussion of the data reduction techniques have been reported by Leonard, et al. [21].

Ideally, measurement of smoke plume trajectory and cross section would be performed using a combination of near field ground observations and long-range measurement from an aircraft following the plume downwind. Near-field ground based measurements were used in this study to measure the initial plume trajectory and cross section over a distance of 1 to 2 km from the source. Both video and still photography images of the initial rise of the smoke plume from the pan were recorded. Distances on these images were scaled from known distances between fixed objects in the field of view.

Since it was not always practical to view the smoke plume perpendicular to the direction of flow, adjustments for oblique viewing angles were made during the data analysis. Figure 11 shows the geometric correction to the observed plume length from a camera at an oblique angle to the wind-blown plume direction. The true plume length (a') is calculated from the observed length (a) as:

$$a' = a/\sin\beta \quad (5)$$

where β is the angle between the nominally crosswind camera view and the smoke plume centerline direction.

The plume radius as a function of distance from the source was measured as part of the analysis. At selected segments of the plume (see figure 12), the radius of the plume was determined at seven locations equidistant along the plume centerline. The

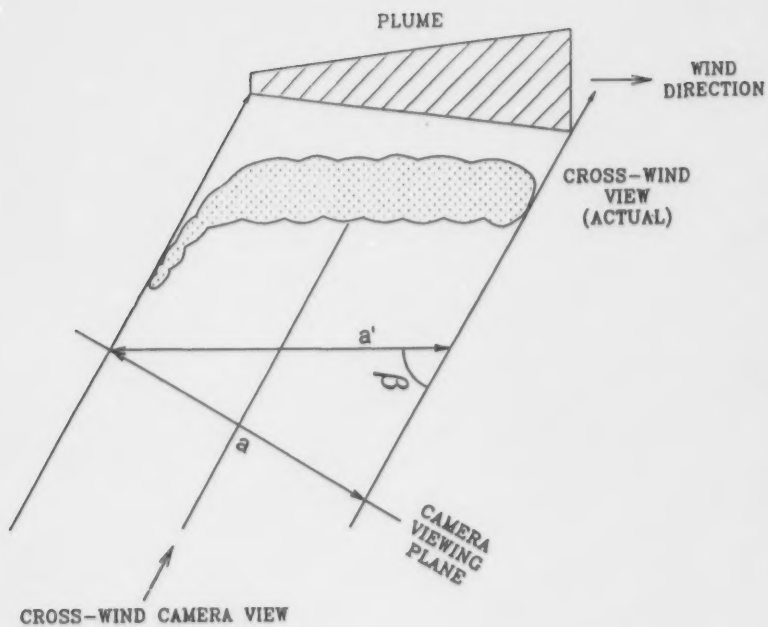


Figure 11. Geometric correction for plume length when observed from an oblique angle

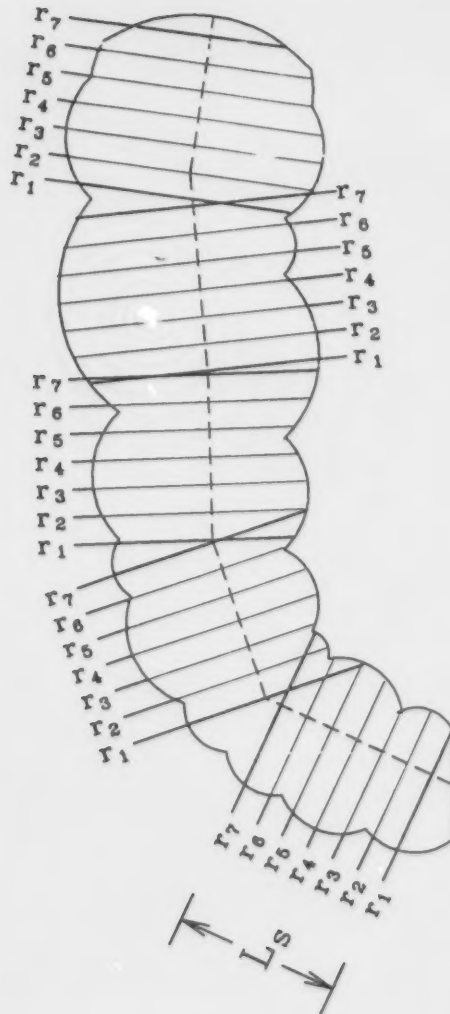


Figure 12. Segments used to calculate plume volume

highest and lowest values were ignored, and the remaining five values were averaged as the best estimate for the radius of that segment. Each segment can be approximated as a cylinder with radius equal to the average radius of the segment, and length equal to the length of the segment. The volumes of the segments can be added together over the entire length of the plume to estimate the total plume volume as:

$$V_p = \sum_{n=1}^N \pi r_n^2 l_n \quad (6)$$

where V_p = Volume of the plume
 n = Segment number
 N = Total number of segments
 r = radius of a cylindrical segment
 l = length of a cylindrical segment

Of the experiments in which measurements were made, mesoscale burn 5/30 provided data on plume trajectory for the largest distance from the pan. As listed in table 5, for this burn the wind direction was from the south-south-east at 170 degrees from magnetic north. The nominal wind speed was 3 m/s at 2 m above ground and 6.2 m/s at 48 m above ground. The crosswind camera recording the plume images was located 3500 m from the pan to the north-east, 70 degrees from magnetic north (across Mobile Bay). Therefore, the crosswind camera was nearly perpendicular to the plume direction. The angle (β) between the camera viewing direction and the plume was 80 degrees. Figure 13 shows a sequence of plume photographs taken from the crosswind camera and the corresponding digitized images at one minute intervals for the first five minutes after ignition. This shows good agreement between the visual plume and the images used for digital analysis. Figure 14 shows digitized images of the plume used for volume and trajectory analysis over the first 600 s after ignition.

Table 17. Initial smoke plume characteristics for mesoscale burn 5/30

Elapse Time (s)	Height (m)	Distance (m)	Volume (m ³ x 10 ⁶)	Volume Rate of Change (m ³ /s x 10 ⁶)
120	160	430	1.8	0.015
240	380	730	10.4	0.072
360	480	1130	58	0.39
480	660	1350	130	1.1
600	780	1820	380	3.2

Table 17 summarizes the results for plume rise, plume volume, and rate increase in plume volume. Measured plume rise heights for the first 600 s after ignition are

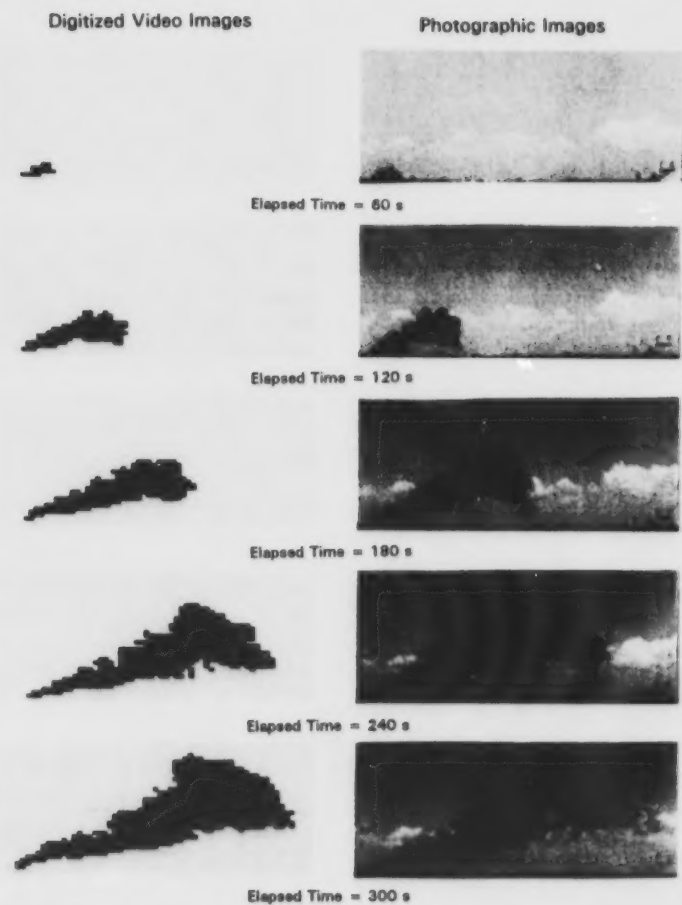
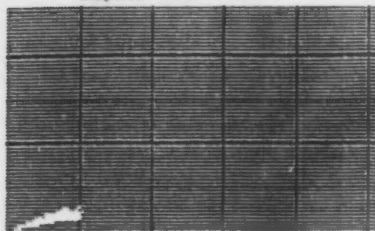


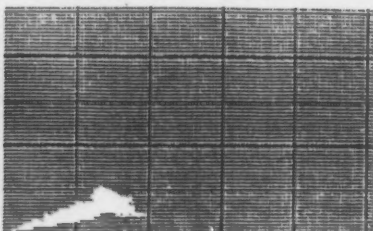
Figure 13. Plume photographs and corresponding digitized images for mesoscale burn 5/30

LINES = 500 m

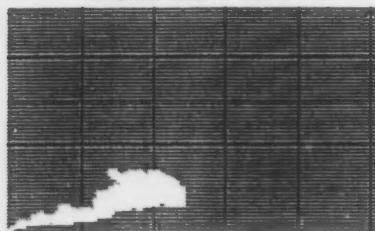
Elapsed Time = 120 s



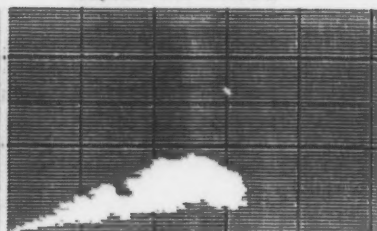
Elapsed Time = 240 s



Elapsed Time = 360 s



Elapsed Time = 480 s



Elapsed Time = 600 s



Figure 14. Digital images used in analysis of mesoscale burn 5/30

plotted in figure 15. At 600 s after ignition the leading edge of the smoke plume had risen to 780 m and traveled 1800 m downwind from the pan. The estimated total volume of the plume at 600 s after ignition was $3.8 \times 10^8 \text{ m}^3$. At that time, the total volume of the smoke plume was increasing at a rate of $3.2 \times 10^6 \text{ m}^3/\text{s}$. This rate of volume increase is largely the result of mixing of smoke particulate in the plume with surrounding air as opposed to the injection of newly formed smoke particulate from the burning crude oil. Table 18 lists the radii of the plume for various downwind distances as determined from analysis of the digitized image of the plume 10 minutes after ignition. These data show the expansion of the smoke plume depth from 40 m near the source to 820 m near the leading edge, 1820 m downwind from the source.

Table 18. Height and radii of the smoke plume 10 minutes after ignition for mesoscale burn 5/30

Downwind Distance (m)	Centerline Height (m)	Effective Diameter (m)
0	0	0
110	40	40
210	80	130
320	120	230
430	160	320
540	200	420
640	240	400
750	310	610
860	380	540
970	440	460
1070	510	480
1180	580	550
1290	640	640
1390	670	730
1500	700	820
1610	730	780
1720	750	720
1820	780	820

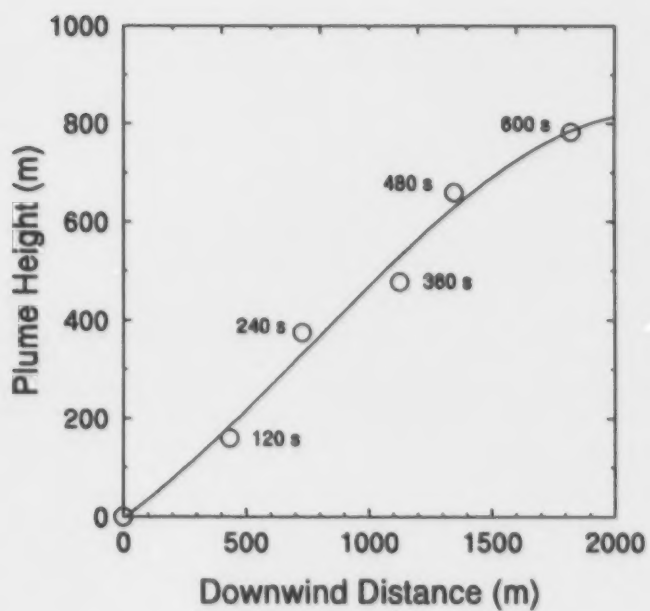


Figure 15. Plume height vs downwind distance for mesoscale burn 5/30

SMOKE PLUME TRAJECTORY MODELING -- LES MODEL

A principal concern in the decision to use in-situ burning as an oil spill mitigation technique is the anticipated trajectory of the plume and the settling out of particulates. The smoke plume trajectory model presented earlier [11] has been generalized to include the capability to describe the rising thermally dominated portion of the smoke plume as well as the descent of the cool, negatively buoyant smoke. A simplified description of the mean thermal stratification of the atmosphere is also included. The wind in the undisturbed atmosphere is still assumed to be uniform on average, but the small scale random eddy motion induced by the natural turbulence in the atmosphere is now represented by an effective "eddy viscosity". A computer code based on an existing enclosure fire simulation program [22] has been developed to implement the model. The resulting code, called LES for Large Eddy Simulation, can be readily generalized to include realistic time averaged ambient temperature and wind profiles in the atmosphere. A summary of the basic assumptions built into the current version of the LES code are given below. This is followed by a summary of the mathematical model which follows from these assumptions. Finally, results showing the full plume trajectory as well as the particulate deposition footprint on the ground as predicted by the model are shown. Comparisons with data obtained in the mesoscale burns are made where appropriate.

We assume that the plume may be described in terms of the steady state physical location of the heated gas and particulate matter introduced by the continuously burning fire into the atmosphere. For this purpose it is not necessary to describe the fire in detail, provided that the overall rate of heat release and the fraction of the fuel converted to particulate matter are known, and the initial plume structure within a few flame lengths of the firebed is not of interest. The subsequent location of the plume as it is carried downwind is determined by the ambient wind and density profiles in the atmosphere along the trajectory of the plume. Since it is not our objective to calculate the local meteorology, it is assumed that this information is available as well. At present, the model is only able to incorporate a uniform wind and a temperature decreasing linearly with height above ground level. The magnitude of both the temperature rise in the plume and the induced velocity fields are assumed to be small compared to their mean values in the undisturbed atmosphere. Finally, the atmosphere is turbulent even in the absence of the fire. This affects the mixing on scales smaller than the resolution of the calculations performed here. The consequences of the small-scale mixing are represented by a constant eddy viscosity, which is ultimately determined by the turbulent kinetic energy content of the atmosphere at "subgrid" scales. This information must be inferred from either measurements of the undisturbed atmosphere or the plume trajectory.

LES MATHEMATICAL MODEL

Given the assumptions outlined above, the mathematical model of the smoke plume requires a description of the gas temperature T and pressure P , the particulate density ρ_p , and the horizontal (y) and vertical (z) velocity components (v, w) in a plane normal

to the direction (x) of the ambient wind U . It is convenient to divide the temperature and pressure fields into mean background values $T_0(z)$ and $P_0(z)$ respectively plus perturbations to these quantities induced by the plume. Let θ and p be the small perturbations to the temperature and pressure respectively. Similarly, the gas density ρ_g is decomposed into an ambient density ρ_0 and a small thermally induced perturbation. This perturbation is related to the temperature perturbation through the equation of state which is taken in the small disturbance low Mach number form appropriate to this problem:

$$(\rho_g - \rho_0)/\rho_0 = - (T - T_0)/T_0 \quad (7)$$

The ambient density is related to the background pressure through the hydrostatic balance :

$$\frac{dP_0}{dz} = - \rho_0 g \quad (8)$$

The background temperature is taken to be linearly stratified:

$$T_0(z) = T_\infty (1 - z/H) \quad (9)$$

Here, T_∞ is the ground level temperature and H is a length of order 10 km. Thus, over the first 1 or 2 km in altitude, the background temperature changes by only a small fraction of its value at ground level. This, together with equation (8), ensures that the fractional variation of the absolute temperature and density are small if the plume calculation begins a few flame lengths downwind of the firebed. Under these circumstances the equations governing the steady-state downwind evolution of the plume can be written in the Boussinesq approximation as follows:

Conservation of mass

$$\frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (10)$$

Conservation of lateral (y) momentum

$$\rho_e \left(\frac{U \partial v}{\partial x} + \frac{v \partial v}{\partial y} + \frac{w \partial v}{\partial z} \right) + \frac{\partial p}{\partial y} = \mu \left(\frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \quad (11)$$

Conservation of vertical (z) momentum

$$\rho_e \left(\frac{U \partial w}{\partial x} + \frac{v \partial w}{\partial y} + \frac{w \partial w}{\partial z} \right) + \frac{\partial p}{\partial z} + (\rho - \rho_e)g = \mu \left(\frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \quad (12)$$

Conservation of energy

$$\rho_e C_p \left(\frac{U \partial \theta}{\partial x} + \frac{v \partial \theta}{\partial y} + \frac{w \partial \theta}{\partial z} \right) - \frac{w dP_e}{dz} = k \left(\frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2} \right) \quad (13)$$

Conservation of particulate mass

$$\frac{U \partial \rho_p}{\partial x} + \frac{v \partial \rho_p}{\partial y} + \frac{w \partial \rho_p}{\partial z} = 0 \quad (14)$$

The windward component of the velocity U in these equations is taken to be constant and much larger than the velocity components in the lateral and vertical directions. Since U does not change, there is no need for a windward component of the momentum equations. After the first few flame lengths downwind of the firebed, the assumption that the windward component of the velocity is much larger than that induced by the plume is quite realistic.

The quantity μ denotes the effective eddy viscosity in the undisturbed atmosphere. It is used here as a means to represent the small scale mixing induced by the atmospheric turbulence. The eddy viscosity is dependent on the level of turbulence in the atmosphere, and is typically about three orders of magnitude larger than the true molecular viscosity of the air. Note that we are only using this concept to simulate the "subgrid" scale motions; i.e. motions on scales below the 5-10 m range which is the resolution limit for the calculations reported here. The large scale mixing processes, from length scales of 1-2 km down to the resolution limit, are calculated directly. Thus, even with the assumption of an eddy viscosity model for the small scale turbulence, the "large eddy" simulations performed require an ability to simulate flows at quite high Reynolds numbers.

In order to complete the mathematical formulation of the problem, initial and boundary conditions must be specified. Since the details of the firebed are not being simulated, the only quantities that are retained are the overall "conserved" parameters,

the total heat release rate Q and the particulate mass flux M . They are related to the local field variables introduced earlier as follows:

$$\begin{aligned} \int_{-\infty}^{\infty} dy \int_0^{\infty} dz \rho_p C_p \theta U &= Q \\ \int_{-\infty}^{\infty} dy \int_0^{\infty} dz \rho_p U &= M \end{aligned} \quad (15)$$

These quantities do not change as the plume moves downwind from the firebed in the absence of ambient stratification in the atmosphere. Thus, these quantities are preserved for the first several pool diameters downwind and can be specified with consistently chosen temperature and particle density crosswind profiles as the initial conditions for the plume temperature θ and particle density ρ_p . The crosswind velocity components v and w are assumed to be zero initially. This ensures that the velocities in the crosswind plane are induced only by the buoyancy in the plume. The boundary conditions at ground level assume no vertical velocity and no plume induced heat transfer or wind shear at ground level. These assumptions are consistent with the assumed uniformity of the ambient wind and the resolution limits imposed by the available computational resources. They are expressed in mathematical form as:

$$w = \frac{\partial v}{\partial z} = \frac{\partial \theta}{\partial z} = 0 \quad \text{at } z = 0 \quad (16)$$

Finally, the far field conditions in the crosswind plane require that the perturbation temperature vanish and the windward component of the vorticity induced by the plume vanish as y and z approach the edge of the computational domain. The perturbation pressure p at the edge of the computational domain can be determined in a self-consistent way by calculating it from the solution of a Poisson equation obtained by requiring that equation (10) holds everywhere. As a practical matter, however, the difference between applying the boundary condition obtained in this way and simply requiring p to vanish at the computational boundary is negligible in the computations performed to date. Hence, the far field boundary conditions implemented in the present model are:

$$\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} = \theta = p = 0; \quad y, z \rightarrow \infty \quad (17)$$

Note that no boundary conditions are explicitly specified for the particulate density ρ_p . This is due to the fact that equation (14) implies that the particles are advected by the large eddy flow field. Hence, once they are introduced into the flow as part of the initial conditions, no further specification is required or possible. In reality however, when the particulate matter reaches the vicinity of the ground, it settles out and is lost from the atmosphere. This is accounted for in the present model by calculating the particulate density as a large number of discrete parcels (Lagrangian

elements) that are carried about by the fluid. Any element that arrives within one computational cell of the ground is within the resolution limits of the calculation of having settled out of the atmosphere. It is then removed from the computation and the location where it settled out of the atmosphere recorded. In this way the "footprint", the distribution on the ground of the particulate matter that has settled out of the atmosphere, can be calculated.

Since the computations that must be performed to solve these equations are quite large, the equations are made nondimensional so that the maximum amount of information can be extracted from each run. The dependent and independent variables are scaled as follows:

$$\begin{aligned}
 \theta/T_\infty &= (Q/C_p T_\infty \rho_\infty U L^2) \hat{\theta}(\hat{x}, \hat{y}, \hat{z}) \\
 \rho/\rho_\infty &= (M/\rho_\infty U L^2) \hat{\rho}_p; p = \rho_\infty V^2 \hat{p} \\
 (v, w) &= V(\hat{v}, \hat{w}); V = (Qg/C_p T_\infty \rho_\infty U L)^{1/2} \\
 X &= (UL/V) \hat{x}; L = (QH/C_p T_\infty \rho_\infty U \beta)^{1/3} \\
 \beta &= \left(\frac{(\gamma-1)gH}{C_p^2} - 1 \right); C_p^2 = \gamma R T_\infty \\
 (y, z) &= L(\hat{y}, \hat{z}) \\
 R_p &= \rho_\infty V L / \mu; P_r = \mu C_p / k
 \end{aligned} \tag{18}$$

The length scale L introduced in equation (18) replaces the arbitrary length used to describe the initial extent of the descending particle plume in [11]. Physically, it is a measure of the height at which the thermal plume will equilibrate with the atmosphere. Note that it depends upon the stability of the atmosphere which is measured by the value of the parameter β . When β is positive, the atmosphere is stable and the plume will reach a maximum height of order L . If β is not positive, the lower atmosphere is not stable and the plume will rise to high altitudes and its fate will be determined by the large scale regional and national weather patterns. In that case the model cannot predict the subsequent deposition pattern of the particulate matter. Note also that the plume model also relies for its validity upon the assumption that the velocity V used to scale the crosswind components of the velocity field in equation (18) is much smaller than the windward velocity component U . This seems to be true for the calculations performed to date.

The dimensionless form of the conservation laws are:

$$\begin{aligned}
 \frac{\partial \hat{v}}{\partial \hat{y}} + \frac{\partial \hat{w}}{\partial \hat{z}} &= 0 \\
 \frac{\partial \hat{v}}{\partial \hat{x}} + \hat{v} \frac{\partial \hat{v}}{\partial \hat{y}} + \hat{w} \frac{\partial \hat{v}}{\partial \hat{z}} + \frac{\partial \hat{p}}{\partial \hat{y}} &= \frac{1}{R_e} \left(\frac{\partial^2 \hat{v}}{\partial \hat{y}^2} + \frac{\partial^2 \hat{v}}{\partial \hat{z}^2} \right) \\
 \frac{\partial \hat{w}}{\partial \hat{x}} + \hat{v} \frac{\partial \hat{w}}{\partial \hat{y}} + \hat{w} \frac{\partial \hat{w}}{\partial \hat{z}} + \frac{\partial \hat{p}}{\partial \hat{z}} + \frac{\hat{p}}{\alpha} - \hat{\theta} &= \frac{1}{R_e} \left(\frac{\partial^2 \hat{w}}{\partial \hat{y}^2} + \frac{\partial^2 \hat{w}}{\partial \hat{z}^2} \right) \\
 \frac{\partial \hat{\theta}}{\partial \hat{x}} + \hat{v} \frac{\partial \hat{\theta}}{\partial \hat{y}} + \hat{w} \frac{\partial \hat{\theta}}{\partial \hat{z}} + \hat{w} &= \frac{1}{P_r R_e} \left(\frac{\partial^2 \hat{\theta}}{\partial \hat{y}^2} + \frac{\partial^2 \hat{\theta}}{\partial \hat{z}^2} \right) \\
 \frac{\partial \hat{p}_p}{\partial \hat{x}} + \hat{v} \frac{\partial \hat{p}_p}{\partial \hat{y}} + \hat{w} \frac{\partial \hat{p}_p}{\partial \hat{z}} &= 0
 \end{aligned} \quad (19)$$

Finally, the associated initial and boundary conditions take the form:

$$\begin{aligned}
 \hat{p}_p &= \hat{p}_i(\hat{y}, \hat{z}); \hat{\theta} = \hat{\theta}_i(\hat{y}, \hat{z}); \hat{v} = \hat{w} = 0 \text{ at } \hat{x} = 0 \\
 \iint d\hat{y} d\hat{z} \hat{p}_i(\hat{y}, \hat{z}) &= 1; MC_p T J Q = 1/\alpha \\
 \iint d\hat{y} d\hat{z} \hat{\theta}_i(\hat{y}, \hat{z}) &= 1 \\
 \hat{w} = \frac{\partial \hat{v}}{\partial \hat{z}} = \frac{\partial \hat{\theta}}{\partial \hat{z}} &= 0 \text{ at } \hat{z} = 0 \\
 \frac{\partial \hat{w}}{\partial \hat{y}} - \frac{\partial \hat{v}}{\partial \hat{z}} = \hat{p} = \hat{\theta} &= 0; \hat{y}, \hat{z} = \infty
 \end{aligned} \quad (20)$$

Note that in these variables the conservation laws depend only upon the Reynolds and Prandtl numbers, which characterize the ratio of the relative effectiveness of the large scale transport to the small scale mixing in the atmosphere, and upon the ratio $Q/(MC_p T_\infty)$, which characterizes the ratio of the positive thermal buoyancy to the negative particulate buoyancy. The details of the initial crosswind profiles serve only to characterize the overall dimensions of the firebed, and are quickly washed out as the plume mixes with the atmosphere.

LES COMPUTED RESULTS

The equations and boundary conditions described above are solved in the LES using finite difference techniques described in [22]. The computational domain is taken to be one unit (in L) high and two units in width. It is divided into a rectangular grid 256 cells high and 512 cells wide for the calculations described below. The Reynolds number employed in the simulation is 20,000, which is within the resolution limits of the grid. The calculation proceeds downwind a distance of 15 units in UL/V , which is enough to ensure that at least 90 percent of the particulate matter injected into the atmosphere in the simulation has settled out. The number of downwind steps required to carry out the computation cannot be prescribed a priori, but is determined

by the numerical stability requirements of the underlying algorithm. For the calculations described below, a minimum of about 6000 steps is required. The particulate matter is represented by 6000 discrete Lagrangian elements which are carried about by the combination of atmospheric and buoyancy induced winds. The particles are not passive; indeed it is their collective negative buoyancy which ultimately causes them to settle out of the atmosphere. They are injected randomly in the vicinity of the firebed with zero initial velocity, and tracked until they reach a computational cell near the ground where they are removed. This final distribution of the locations of the removed particles is the footprint.

The computations have been carried out on an IBM RISC System 6000 model 550.¹ Using a grid of the size described above, the calculations require about 5 seconds to complete a step in the downwind direction. Approximately 30 megabytes of memory are required to accommodate the entire calculation and the associated output buffers. It should be noted that this is less than half the available memory on the minimum available configuration of this particular computer. In fact, the mathematical model and the associated LES have been developed with the idea that they can be used on a variety of high performance workstations available from several computer manufacturers.

Figures 16 and 17 illustrate results obtained from a simulation using data from mesoscale burn 5/30. The burn generated an estimated 0.5 kg/s soot particulate mass flux in a fire whose convective heat release rate is estimated at 110 MW. The wind velocity was measured at 6 m/s. The computational domain is then 1.6 km high, 3.2 km wide, and 258 km in the downwind direction.

Figure 16 shows the locations of the particle plume at eleven stations downwind of the fire extending out the first 190 km downwind from the fire. The plume is initially dominated by the large heat input from the fire and the plume rises rapidly to a maximum height of about 0.8 km. The smoke plume gradually separates from the thermal plume, however, once the stabilized height is reached. This is due to a combination of small scale mixing processes and the stratification of the atmosphere. After the separation of the thermal and particle plumes, the negatively buoyant particle plume gradually descends to the ground. Near ground level the lateral spreading is enhanced by the interaction of the vorticity in the plume with the ground plane. Finally, in the final 6.25 m (the size of one computational cell) the particulate matter is assumed to settle out of the atmosphere and is removed from the computation. The reader is reminded to note the difference in downwind and crosswind scales in figure 16; even with the enhanced spreading near the ground the plume is a long, slender object.

Figure 17 shows the computed footprint in the ground plane out to 258 km, where over ninety percent of the particulate matter has settled out of the plume. The particles are distributed in long striations which are caused by the ground induced vortex motion which produces highly organized motion near the surface. This plot indicates that the density distribution on the ground is far from uniform, so that the average value of 1.5 mg/m² over the whole footprint is not a reliable indicator of the

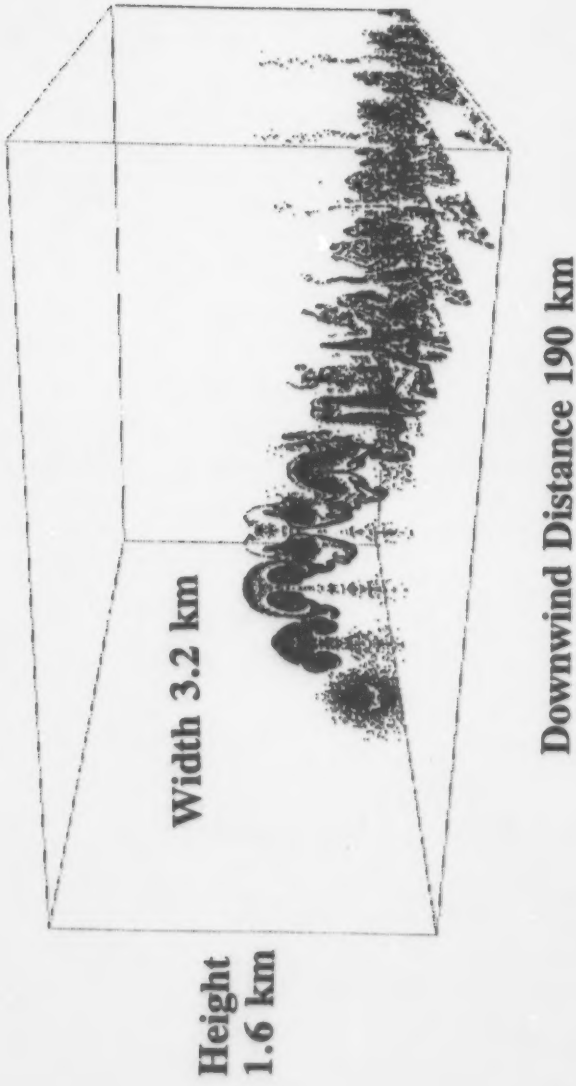


Figure 16. LES prediction of downwind particulate distribution in the air

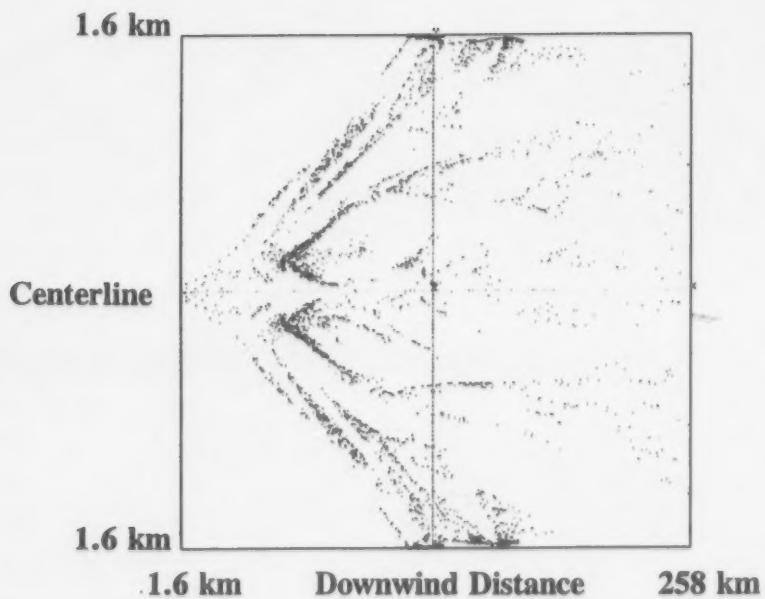


Figure 17. LES prediction of the pattern of downwind particulate deposition.



Figure 18. View of initial plume flow above pan in mesoscale burn 5/30

local particle deposition. Only a few percent of the ground level computational cells are actually occupied by particles. Again, the reader should be aware of the difference between the crosswind and downwind length scales when studying this figure.

Future work will focus on incorporating a more realistic description of the plume environment into the model. The atmospheric wind and temperature profiles will be made more realistic and some attempt to incorporate terrain effects into the model will be made. This will ultimately require an interface between this computer code and a local to regional scale meteorology model. The computational task will undoubtedly be larger than that presently required, but that should be more than offset by the explosive growth of inexpensive computing power.

SMOKE PLUME TRAJECTORY MODELING - EPA SCREEN MODEL

The NIST LES model provides detailed information on the plume trajectory, dispersion, and particulate deposition. The initial trajectory of the smoke plume agreed with measurements, but measurements were only obtained over a small portion of the predicted distance of the plume. No measurements of long range particulate deposition were attempted in the mesoscale burns, so these predictions remain unvalidated. Even though experimental measurements are not available, it is interesting to compare predictions of the NIST LES model to the widely used, and EPA approved, SCREEN model [23].

SCREEN is based on the classical diffusion equation, and thus provides near Gaussian distribution of combustion product concentration at specified locations downwind from the source as a function of a variety of input parameters, including wind speed, atmospheric stability class (an indicator of atmospheric turbulence based on solar elevation angle, cloud cover, cloud ceiling height and wind speed), particulate emission rate, and total heat release rate. SCREEN can run a full range of meteorological conditions, which consists of various combinations of wind speed and stability class.

SCREEN has three ways to specify the emission, including the point source, area source and flare source options. While none of them is exactly suited to predictions of large pool fires, the flare option furnishes the best means for simulating the burn. Although SCREEN was originally designed for modelling smoke plumes generated by low-energy (low-buoyancy) fires emitted from smoke stacks, it may be adaptable to high-energy crude oil fires as long as the user provides a realistic value for the heat release rate.

Results of the SCREEN calculations are subject to the following conditions that are built in assumptions of the model:

With the flare option, plume rise is calculated from the top of the flame (the effective release height); the flame is assumed to be bent at a 45 degree angle.

Heat loss by radiation is 55% of the total heat released; the remaining 45% becomes the convective heat release used in the calculations. (In the LES model calculation the radiative loss was set at 40% which is generally used for highly radiative flames).

With the choice of the flare option, the following values are automatically assigned by the model:

Effective gas exit velocity = 20 m/s
Effective gas exit temperature = 1273 K
Ambient air temperature = 293 K

Once the stability class and wind speed are specified, they are assumed to obtain over the length of the plume; atmospheric inversions cannot be treated.

SCREEN has been used to model the smoke plume flow for the mesoscale burn 5/30. The parameter values used in the calculation are the following:

Smoke particulate emission rate = 0.5 kg/s (smoke particulate).

Flare stack height = 0.0 (ground level burn).

Effective release height = 20.48 m (the calculated height of the flame top).

Total heat release = 245 MW (based on an effective heat of combustion of 41.9 MJ/kg); 45% of this value (110 MW) is the convective heat release rate.

Receptor height = varied.

Based on the weather conditions at the test site, stability class C (strong incoming solar radiation, surface wind speed of 6 m/s) was assumed (see figure 18).

The results of the modelling run are presented in figures 19 through 21.

Figure 19 shows the downwind variation of maximum smoke concentration at ground level. These values occur below the plume centerline only and represent an average taken over one hour. As it is presently constituted, SCREEN has no means for calculating the settling out and subsequent ground deposition of smoke particulates. It assumes that the smoke is carried downstream as a neutrally buoyant mass that diffuses vertically and laterally in a Gaussian manner about the plume centerline. In addition SCREEN provides predictions for a maximum of 100 km downwind. The predicted ground level concentrations if interpreted as a deposition are much lower

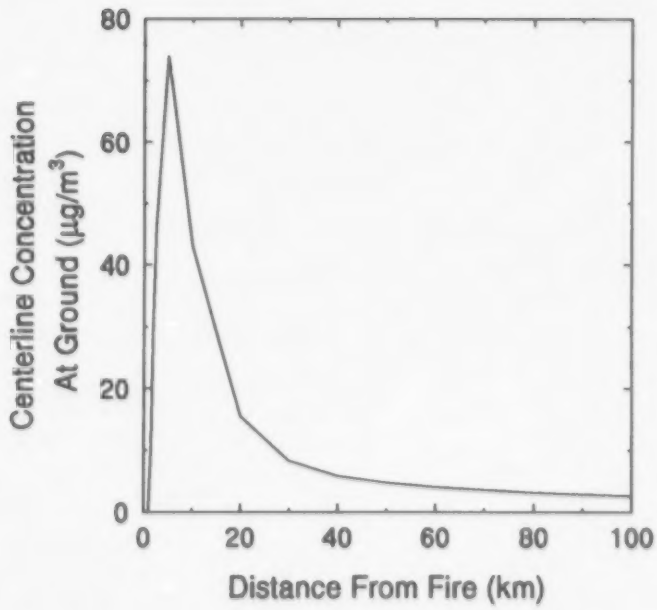


Figure 19. Screen prediction of ground level smoke particulate concentration

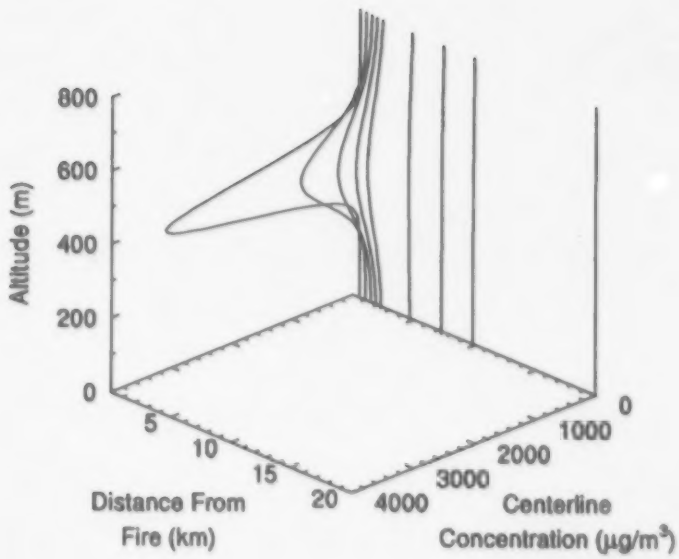


Figure 20. SCREEN prediction of centerline smoke particulate concentration in air

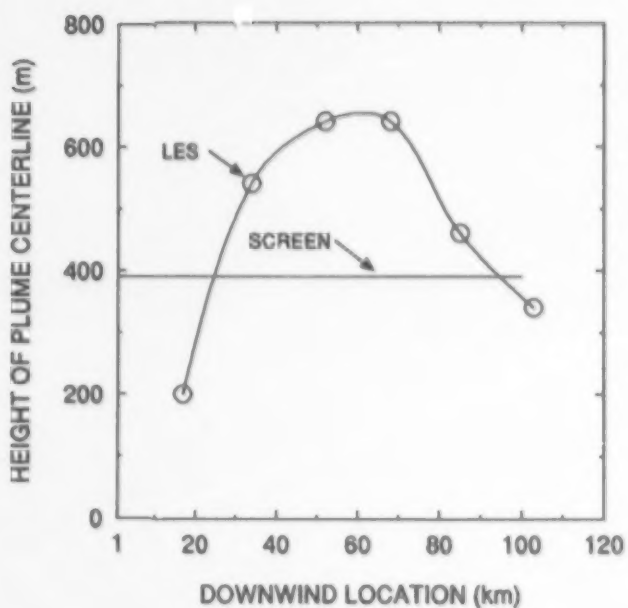


Figure 21. SCREEN and LES predictions of centerline plume height

than would be expected from the results of the LES model which predicts an average deposition of 1.5 mg/m^2 . The smoke diffusion process is best illustrated in figure 20, which shows the vertical dispersion of smoke about the plume centerline with downwind distance; it is clear that most of the smoke is still well above ground, even far downwind. Finally, figure 21 shows the smoke plume height as a function of distance downwind. SCREEN is incapable of calculating the actual rise trajectory of the smoke plume and provides only a final constant plume height as compared to the rise and fall of the smoke plume predicted by LES.

CONCLUSIONS

For the mesoscale experiments, the average burning rate for fresh Louisiana crude oils at 17.2 m effective diameter was only 7% greater than that measured at the largest laboratory scale of 2.0 m. This indicates that with small corrections the burning rates of large laboratory fires can be used to estimate the expected steady burning of larger fires. The wind speed did not appear to affect the average burning rate but did contribute to variations in burning extinction. The recommended value to use for the burning rate of thick layers of fresh crude oils on water is $0.047 \pm 0.01 \text{ kg/s/m}^2$ ($4.9 \pm 1 \text{ gal/hr/ft}^2$).

It was generally found that well over 90 percent of the fresh oil was consumed in the pan burns. In addition, the residue from the primary burn could be corralled and burned with the addition of a kerosene as an ignitor.

Smoke yield from fresh crude oil fires depends on diameter. In 0.085 m diameter laboratory fires the minimum smoke yield of 0.05 for Murban and 0.06 for Louisiana crude oils were measured. At 2.0 m diameter the smoke yield for the Murban crude oil was a significantly greater, 0.14, as measured in the large laboratory pan burns at FRI. Measurement from the mesoscale experiments are more scattered than the laboratory measurements, but the value of 0.13 ± 0.01 smoke yield represents most of these measurements. The recommended value for smoke yield from large the burning of thick layers of fresh Louisiana crude oil is 0.13. From laboratory burns it is expected that the Murban crude oil would have a higher smoke yield than the Louisiana crude oil if burned at mesoscale.

The size distributions of aerodynamic effective diameters for the smoke particulate were measured in the 2.0 m diameter laboratory and mesoscale fires. Most of the particulate mass was below $10 \mu\text{m}$ in diameter as measured with a cascade impactor. There is a shift of particulate size distribution to larger size particles from the larger diameter fire.

Prediction of the smoke plume trajectory and particulate deposition show that because the smoke particulate is distributed over great distances from the fire, the local concentration beyond the near fire region (which is not calculated) is small. The results from the LES and SCREEN models indicate the strength of the LES model over the EPA approved SCREEN model for predicting particulate deposition. The

LES model was written specifically to be able to predict particulate deposition and requires substantial computer resources whereas the SCREEN model was developed as a screening tool for general emissions. The LES model allows particulate to settle and deposit on the ground whereas the SCREEN model does not. As a result, SCREEN predicts the maximum downstream concentration of product remains at fixed altitude and particulate only reaches ground level through diffusion. The product that reaches the ground does not deposit there but continues to diffuse downstream.

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In Situ Burning via Towed Boom of Oil Spilled at Sea

by

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Operational guidance for the efficient use of combustion in the cleanup of a surface oil film, formed as a result of a spill at sea, is sought by approximate analysis. In remediation by burning, the spilled oil itself provides the energy for its cleanup. Attention is focused on situations holding relatively far from the source of the spill and/or relatively long after the spill: the oil is taken to have so dispersed that the thickness of the film is on the order of a few millimeters. Under such conditions, the oil film is unlikely to burn without the use of multiple towed booms, each boom spreading its already-ignited, localized fire to continuously collected, previously unignited portions of the oil film. A simple, quasisteady, two-dimensional analysis suggests efficient values for the tow speed and the tow-line length as functions of such parameters as the oil density, oil-film thickness, oil burn/evaporation rate, etc. The analysis leads to specific suggestions for apparently unreported laboratory experiments that may be informative prior to at-sea operation.

INTRODUCTION

We consider an option for the removal of oil spilled at sea. The option includes containment by towed booms and combustion of the oil (Fig. 1) [1-7]. It seems unlikely that the formation of soot and other hydrocarbon products [3,4,8], for which there may be methods of mitigation [9,10], could outweigh the advantage of this in situ reduction (even elimination) of the oil. Alternative methods that remove, as distinguished from redistribute and/or disperse, the spilled oil entail large requirements for collection, storage, transportation, and disposal [1].

Accordingly, we analyze the fluid dynamics (including the consequences of mass conservation) of the combustion phenomena in order to obtain estimates of suitable operational parameters.

We note that extensive modeling, experiments, and observations are available concerning the spreading and fate of oil spilled at sea in the absence of countermeasures [11-13].

THE DYNAMICS OF THE OIL LAYER

We adopt a two-dimensional idealization of the real three-dimensional configuration (Fig. 1). As is shown in Fig. 2, we fix our coordinates in the boom so that the flow (relative to the boom, of course) is in the x direction and is independent of time.

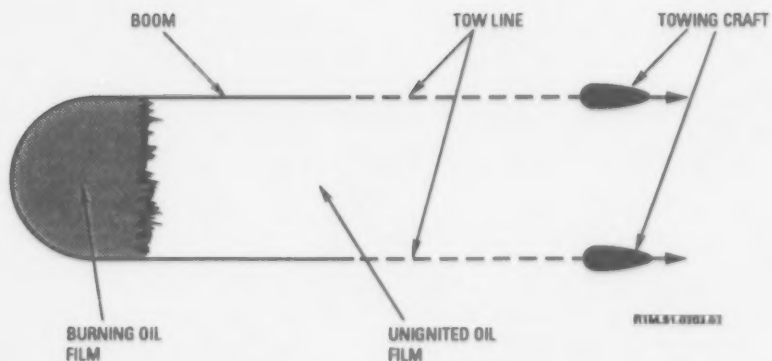


Figure 1. Plan view, not to scale, of a typical oil-film-"herding"-and-burning operation at sea, including a towed U-configured boom.

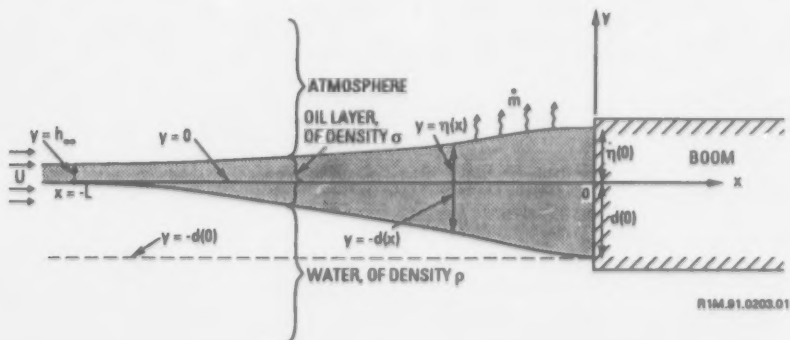


Figure 2. Schematic for a quasisteady, two-dimensional model of the burning [with oil-surface-regression rate $\dot{m}(x)$, typically on the order of 0.1 mm/s] of an oil slick of ambient thickness h_{∞} and of density σ . In the frame of reference of a towed impervious boom, the ambient oil and water at $x \leq -L$ approach at the towing speed U .

The vertical coordinate, y , has its origin at the altitude of the oil-water interface upstream of the burning region, which is adjacent to the boom. For operating parameters of interest, the oil layer is very thin compared with the range of x over which the dynamics are at issue, and thus the slope of both the oil-atmosphere surface, $y = \eta(x)$, and the oil-water interface, $y = -d(x)$, is very small. It is consistent with the foregoing to adopt a hydrostatic approximation for the vertical-momentum balance. We use the notation indicated in Fig. 2, so that the equation which represents this approximation of the vertical-momentum balance is (g is the magnitude of the gravitational acceleration)

$$p_y + \sigma g = 0 \quad \text{in} \quad -d(x) < y < \eta(x). \quad (1)$$

Here σ is the density of the oil and the datum of the pressure p is taken as follows:

$$p = 0 \quad \text{at} \quad y = \eta(x). \quad (2)$$

It follows that

$$p(x, y) = \sigma g [\eta(x) - y], \quad \text{in} \quad -d(x) < y < \eta(x), \quad (3)$$

and

$$p_x = \sigma g \eta'(x), \quad \text{in} \quad -d(x) < y < \eta(x). \quad (4)$$

It is also consistent with the foregoing to ignore the horizontal acceleration of the oil so that (with μ_0 denoting the dynamic viscosity of the oil)

$$p_x = \mu_0 u_{yy}. \quad (5)$$

Since p_x is independent of y from Eq. 4, u is quadratic in y . The (almost horizontal) velocity of the oil-water interface at $y = -d(x)$ is denoted by $u_1(x)$. The velocity gradient in the vertical direction, $u_y(x, y)$, must vanish at $y = \eta(x)$, and therefore

$$u(x, y) = u_1(x) - \frac{\sigma g \eta'(x)}{2\mu_0} [y + d(x)][d(x) + 2\eta(x) - y]. \quad (6)$$

Mass conservation in $-L < x < 0$, $-d(x) < y < \eta(x)$, where $\eta'(x) = 0$ for $x \leq -L$, is given by

$$u_x + v_y = 0. \quad (7)$$

Since $u(0, y) = 0$ because the boom is impervious,

$$\begin{aligned} \frac{d}{dx} \int_{-d(x)}^{\eta(x)} u(x, y) dy - [\eta'(x)] u[x, \eta(x)] + d'(x) u[x, -d(x)] \\ + v[x, \eta(x)] - v[x, -d(x)] = 0, \end{aligned} \quad (8)$$

or

$$\int_{-d(x)}^{\eta(x)} u(x, y) dy = \int_x^0 \dot{m}(\delta) d\delta, \quad (9)$$

since

$$\begin{aligned} v(x, \eta) - [u(x, \eta)] \eta'(x) &= \dot{m}(x), \\ v(x, -d) - [u(x, -d)] d'(x) &= 0, \end{aligned} \quad (10)$$

and $\dot{m}(x)$ is the vertical efflux of the pyrolyzing oil (with the dimensions of a velocity). The upstream edge of the combustion zone is at $x = -L$. The result given by Eq. 9 may seem immediately self-evident, but the development assists the exposition.

Somewhat varying empirical data regarding the consumption rate of an oil film on water have been published [3, 6, 11-14]. More data are needed concerning the dependence of the oil burning rate on layer thickness, type of oil, and wind speed if the model results are to be definitive; this subject is briefly readdressed below.

If the integral on the right-hand side of Eq. 9 is denoted $M(x)$, then mass conservation [i.e., Eq. 9] implies $M(-L) = [u_1(-L)][\eta(-L)]$, since $u(-L, y) = u_1(-L)$ and $d(-L) = 0$ by definition. Substitution of Eq. 6 in Eq. 9 gives

$$(\eta + d) u_1 - \frac{\sigma g \eta'}{3\mu_0} (\eta + d)^3 = M(x). \quad (11)$$

We collect some of the above, append several bits of notation, and add some simple consequences of the foregoing analyses of the oil layer:

$$p[x, -d(x)] = \sigma g(\eta + d), \quad (12)$$

$$\tau_{xy}[x, -d(x)] \equiv \mu_0 u_y[x, -d(x)] = -[\sigma g \eta'(x)][d + \eta], \quad (13)$$

$$u_1(-L) \equiv U, \quad (14)$$

$$\eta(-L) \equiv h_\infty, \quad (15)$$

and

$$d(-L) = 0. \quad (16)$$

THE DEEP-WATER DYNAMICS

The motion in the deep water, i.e., the perturbation in velocity from its upstream horizontal value, U , is driven by the friction that the oil exerts on the water at the oil-water interface. We can expect with confidence that the perturbation

velocity is not greater than U itself. Accordingly, the "Bernoulli correction" to the hydrostatic pressure in the water can be no larger than that in the oil. It is thereby consistent with the analysis of the previous section (wherein the Bernoulli corrections were ignored) to adopt an Oseen approximation [18] to the dynamic balance, and to locate the oil-water interface at a depth that is consistent with the considerations set forth in this paragraph and with

$$\frac{\partial p}{\partial y} = -\rho g \quad \text{in } y < -d(x), \quad (17)$$

where ρ denotes the density of the water. Thus, in $y \leq -d(x)$ and in $x \leq -L$, the pressure in the water, p_{water} , is given by

$$p_{\text{water}}(-L, y) = \sigma g h_m - \rho g y. \quad (18)$$

But

$$p_{\text{water}}(x, y) = \sigma g [\eta(x) + d(x)] - \rho g (y + d). \quad (19)$$

Equating the two expressions gives

$$\eta = \frac{\rho - \sigma}{\rho} (\eta + d) + \frac{\sigma h_m}{\rho}, \quad (20)$$

and

$$\eta' = \frac{\rho - \sigma}{\rho} (\eta + d)'. \quad (21)$$

The appropriate Oseen model for the perturbation velocity u^* is (since $u_{xx} \lll u_{yy}$)

$$\mu u_{yy}^* - \frac{\rho U}{3} u_x^* = 0 \quad \text{in } y < 0, \quad (22)$$

where μ denotes the viscosity of the water, and since $u^*(x, y) \equiv u(x, y) - U$,

$$u^*(x, 0) = u_1(x) - U. \quad (23)$$

In this formulation we use the usual small-surface-slope approximation wherein (in the notation of this problem) $u^*[x, -d(x)]$ is replaced by $u^*(x, 0)$. The choice of the effective convective speed ($U/3$) in the linearized convective operator of Eq. 22 is standard and well-motivated [18]. Also, in this treatment of the dynamics of the water, we extend the domain to encompass $y < 0$ and $-\infty < x < \infty$. We defer until later the adjustment that will be necessary in order to accommodate the requirement that $u^*(0, 0) = -U$, since $u_1(0) = 0$ because we expect that the oil-water interface intersects the impervious boom (Fig. 2).

The Fourier transform in the coordinate x of Eq. 22 is

$$\mu \bar{u}_{yy}^*(\zeta, y) - \frac{\rho U}{3} \zeta \bar{u}^*(\zeta, y) = 0, \quad (24)$$

where ζ is the transform variable and a super bar signifies a transformed quantity. By the requirement of boundedness, and by use of Eq. 23 to identify the function of integration, solution of Eq. 24 gives

$$\bar{u}^*(\zeta, y) = \left[\bar{u}_1(\zeta) - \frac{U}{1\zeta} \right] \exp \left\{ \left[\frac{\rho U}{3\mu} 1\zeta \right]^{1/2} y \right\}. \quad (25)$$

The stress τ_{xy} is given at $y = 0$ by

$$\tau_{xy}(x, 0) = \mu u_y(x, 0), \quad (26)$$

and its Fourier transform in x is, by Eq. 25,

$$\bar{\tau}_{xy} \equiv \bar{\tau}(\zeta) = \mu \left(\frac{\rho U}{3\mu} \right)^{1/2} \left[\bar{u}_1(\zeta) - \frac{U}{1\zeta} \right]. \quad (27)$$

Inversion of Eq. 27, by use of convolution, gives, in view of Eq. 14,

$$u_1(x) - U = \left(\frac{3}{\rho \mu U} \right)^{1/2} \int_{-L}^x \frac{\tau_{xy}(x_1)}{[\pi(x - x_1)]^{1/2}} dx_1. \quad (28)$$

THE MATHEMATICAL PROBLEM

We now define the following dimensionless variables:

$$w(s) \equiv \frac{u_1(x)}{U}, \quad H(s) \equiv \frac{\eta(x) + d(x)}{h_m}, \quad f(s) \equiv \frac{H(x)}{U h_m}; \quad (29)$$

$$s \equiv \frac{x}{L}, \quad \lambda \equiv \frac{\rho - \sigma}{\rho} \frac{gh_m^3}{3UL\mu_0/\sigma}, \quad K \equiv \frac{\sigma(\rho - \sigma)}{\rho^2} \frac{gh_m^2}{(\mu U^3 L/3)^{1/2}}, \quad (30)$$

where $\nu \equiv \mu/\rho$. The presence of the quantities U and L as multiplicative factors in the denominators of the parameters λ and K is noteworthy.

By use of Eqs. 13, 21, 26, 29, and 30, we may rewrite Eqs. 11 and 28 as

$$\lambda H^3(s) H'(s) = w(s) H(s) - f(s), \quad (31)$$

and

$$w(s) - 1 = -K \int_{-1}^s \frac{H(s_1) H'(s_1)}{[w(s - s_1)]^{1/2}} ds_1. \quad (32)$$

The dimensionless dependent variables w and H must obey the conditions

$$H(-1) = w(-1) = 1. \quad (33)$$

In the absence of pyrolysis and burning, $f(s) = 1$; then, $w(s) = H(s) = 1$, i.e., the volumetric flux per length Uh_∞ accumulates at the boom (and soon overruns and underruns it). There are two more constraints on the system. First, the upstream edge of the combustion zone must proceed to the left (in the natural coordinate system) at speed U . Thus, the operating speed U must be chosen in accord with the firespread rate of the oil layer, which, in turn, depends on the thickness of the layer, the wind speed, properties of the oil, and possibly other factors. Little is known about the firespread rate [3], and data are needed before one can exploit any model of the oil-slick-burning phenomenon. Second, for consistency with Fig. 2, it is also necessary that $w(0) = 0$.

For some values of λ and K , it is a remarkable coincidence that $w(0)$ does become zero. For other cases one must note that the analysis fails in a very small neighborhood of $s = 0$. It is also evident, however, that in so small a region, any adjustment that the velocity field requires can perturb only very locally the overall balance for either the mass or momentum of the oil. Figure 3 is a schematic diagram of the perturbed geometry that would accompany the flow for those values of λ and K for which Eqs. 31 and 32 do not yield $w(0) = 0$, upon integration from $s = -1$ to $s = 0$.

Incidentally, for the convenience of treating only positive values of the independent variable, we sometimes elect to adopt the coordinate t , where

$$t = s + 1, \quad \text{so} \quad 1 \geq t \geq 0. \quad (34)$$

However, we refer to the primary dependent variables as H and w whether we work in the s or t coordinate, because we seek to avoid further proliferation of notation.

Once solution for $H(t)$ is obtained from Eqs. 31-32, $\eta(x)$ is available from Eq. 20, and $d(x)$ follows by subtraction, from the middle relation of Eq. 29.

We concentrate below entirely on the case of a pyrolyzation rate uniform in the domain $1 \geq t \geq 0$, so $f(t) = 1 - t$ for calculations reported here. Again, obtaining further data seems desirable before pursuing alternative distributions [though in all distributions of interest $f(t) = 1$ for $t = 0$ and $f(t) = 0$ for $t = 1$].

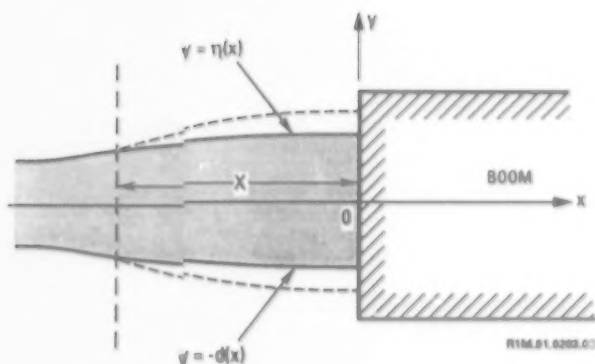


Figure 3. The solid curves delineate the limits of the (shaded) oil layer, $y = \eta(x)$ and $y = -d(x)$, as given by the integration of Eqs. 31-33. When, according to the model, the horizontal velocity component at the oil-water interface exceeds zero at the boom, $x = 0$, then over a distance X , which can be only a few multiples of the vertical expanse $[\eta(0) + d(0)]$ and which is much less than the distance L (Fig. 2), there is a boundary-layer-like modification (not analyzed) such that each of $\eta(x)$ and $d(x)$ is given by its respective dashed-curve counterpart.

SOLUTION

We proceed to identify, by numerical solution, those values of the dimensionless groups λ and K for which practically interesting behavior is obtained. Such behavior is characterized by (1) H increasing monotonically as t increases, such that the value of H at the boom is at least a few multiples of the value of H at $t = 0$; and (2) w decreasing monotonically as t increases, preferably such that w is close to zero at the boom. Then, for practically interesting values of the parameters ρ (water density), σ (oil density), h_m (ambient oil-film thickness), μ_o (dynamic water viscosity), and ν (kinematic water viscosity), via Eq. 30 we infer values for U (tow speed) and L (burning-patch length) from the adopted values of λ and K .

Alternatively, and more directly, we can adopt values for U and L (as well as for ρ , σ , h_m , μ_o , and ν), and thus specify values of λ and K . In choosing values, we recall [from Eqs. 29-30, the definition of $M(x)$ given above, Eq. 11, and Eq. 34] that the value of the regression speed m , such that previously herded oil leaves the layer as fast as freshly herded oil enters the layer (so a steady configuration persists), is given by

$$m = \frac{dM}{dx} = \frac{Uh_m}{L} \frac{df}{dt} + \frac{Uh_m}{L} \quad (35)$$

for $f(t) = 1 - t$. Equation 35 guides the parameter assignments for consistency with oil-layer-burning rate data: according to [6], typically $m \approx 0.06 - 0.07$ mm/s, and according to [5], $m \approx 0.035 - 0.05$ mm/s. We need to ascertain that the system, Eqs. 31-33, has solutions with the desired properties for the values for the groups λ and K implied by the parameter assignments.

We now discuss details of the calculations. From knowledge of $H(t)$ and $w(t)$, from Eq. 31 we compute $H(t + \Delta t)$, where Δt is a very small increment, by holding w fixed at the value $w(t)$, e.g., by the standard fourth-order Runge-Kutta formula; with H known over the $(t, t + \Delta t)$ interval, we then obtain $w(t + \Delta t)$ from a trapezoidal-rule-type integration of Eq. 32. We then repeat the two-step cycle for the next incremental interval in t . We search for a Δt small enough that the overall results are effectively invariant to the step size Δt , rather than iterate for every increment in the independent variable t . For the calculations reported below, $\Delta t = 0.0001$. Incidentally, the integrably singular kernel $K(s - s_1) \equiv [\pi(s - s_1)]^{-1/2}$ in Eq. 32 may be conveniently and accurately modified this:

$$K(s) = \begin{cases} a - bs - cs^2, & 0 \leq s \leq s_0 \\ (\pi s)^{-1/2}, & s_0 \leq s \leq 1, \end{cases} \quad (36)$$

where requiring the continuity of value and slope at s_0 ($\ll 1$) and requiring the equality of the integrals

$$\int_0^{s_0} (a - bs - cs^2) ds = \int_0^{s_0} (\pi s)^{-1/2} ds \quad (37)$$

imply

$$a = \frac{15}{4\pi s_0^{1/2}}, \quad b = \frac{5}{\pi^{1/2} s_0^{3/2}}, \quad c = \frac{9}{4\pi^{1/2} s_0^{5/2}}. \quad (38)$$

Also, we note that, since $H'(0) = w'(0) = 0$, for $f(t) = 1 - t$, as $t \rightarrow 0$, from Eqs. 31-38,

$$H(t) \approx 1 + \lambda^{-1} t^2/2 + \dots, \quad w(t) = 1 - Kat^2/(2\lambda) - \dots \quad (39)$$

Thus, although the solution of Eq. 31 superficially might seem to possess boundary-layer character for $1 \gg \lambda \geq 0$, in fact, the right-hand side vanishes at $t = 0$, in view of Eq. 33 and in view of the constraint that (at $t = 0$) $f(0) = 1$ by definition; that is, the solution of the reduced equation satisfies the boundary conditions. In fact, as $t \rightarrow 1$ and $f(t) \rightarrow 0$, the left-hand side of Eq. 31 tends to balance the first term on the right-hand side, since in general the value of $w(1)$ given by Eqs. 31 and 32 is small but finite. If $w(1) \neq 0$, from Eq. 32,

$$K = \left\{ \int_0^1 \frac{H(t_1) H'(t_1)}{[w(1-t_1)]^{1/2}} dt_1 \right\}^{-1}, \quad (40)$$

so it is not implausible that we find that H is larger as $t \rightarrow 1$ for smaller values of the parameter K , for fixed values of λ . As λ is increased for fixed K , typically we find that $w(t)$ decreases less as t increases from zero to unity.

The nominal parameter assignments are taken to be as follows [5]:

$$\begin{aligned} \nu &= 0.01 \text{ cm}^2/\text{s}, \quad \rho = 1 \text{ g/cm}^3, \quad g = 980 \text{ cm/s}^2, \\ h_0 &= 0.2 \text{ cm}, \quad \mu_0 = 1 \text{ g/(cm s)}, \quad \sigma = 0.934 \text{ g/cm}^3, \\ U &= 26 \text{ cm/s}, \quad L = 1500 \text{ cm}. \end{aligned} \quad (41)$$

These assignments imply that the nominal values of λ and K are:

$$\lambda = 4.13 \times 10^{-6}, \quad K = 8.15 \times 10^{-3}, \quad \dot{h} = -3.47 \times 10^{-3} \text{ cm/s}. \quad (42)$$

In results reported here, all parameters taken on their nominal values in the absence of explicit statement to the contrary, and the independent variable is taken to be t . For the nominal case $H(1) \approx 17.8$, $w(1) \approx 0.01$. Figure 4 presents results for $w(t)$ for the following cases:

(1), nominal case [see Eqs. 41 and 42];

$$(2), U = 52 \text{ cm/s}, \quad \lambda = 2.06 \times 10^{-6}, \quad K = 2.88 \times 10^{-3},$$

$$\dot{h} = -6.93 \times 10^{-3} \text{ cm/s};$$

$$(3), L = 750 \text{ cm}, \quad \lambda = 8.26 \times 10^{-6}, \quad K = 1.15 \times 10^{-2},$$

$$\dot{h} = -6.93 \times 10^{-3} \text{ cm/s};$$

$$(4), h_0 = 0.4 \text{ cm}, \quad \lambda = 3.30 \times 10^{-5}, \quad K = 3.26 \times 10^{-2},$$

$$\dot{h} = -6.93 \times 10^{-3} \text{ cm/s};$$

$$(5), \sigma = 0.82 \frac{\text{g}}{\text{cm}^3}, \quad \lambda = 9.89 \times 10^{-6}, \quad K = 1.95 \times 10^{-2},$$

$$\dot{h} = -3.47 \times 10^{-3} \text{ cm/s};$$

and

$$(5), \rho_0 = 2.0 \frac{\text{g}}{\text{cm}^3}, \lambda = 2.06 \times 10^{-6}, \kappa = 8.15 \times 10^{-3},$$

$$\dot{m} = -3.47 \times 10^{-3} \text{ cm/s.}$$

(43)

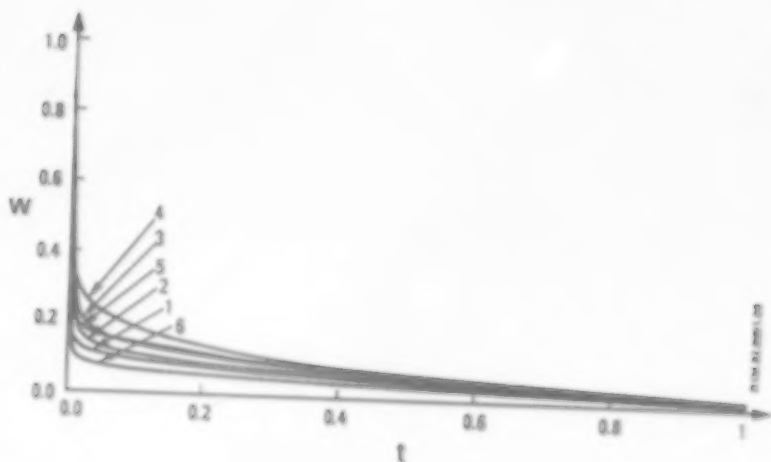


Figure 4. The normalized oil-water-interface speed w as a function of the nondimensional spatial coordinate t , for the cases of Eq. 43.

Figure 5 presents the corresponding results for $H(t)$ for the cases of Eq. 43. Figure 6 presents results for $w(t)$ for most of the following cases, for all of which $\dot{m} = -3.47 \times 10^{-3}$ cm/s, the nominal value:

(1), nominal case [see Eqs. 41 and 42];

(7), $U = 52$ cm/s, $L = 3000$ cm, $\lambda = 1.03 \times 10^{-6}$,
 $\kappa = 2.04 \times 10^{-3}$;

(8), $U = 13$ cm/s, $L = 750$ cm, $\lambda = 1.65 \times 10^{-5}$,
 $\kappa = 3.26 \times 10^{-2}$;

(9), $U = 52$ cm/s, $h_0 = 0.1$ cm, $\lambda = 2.58 \times 10^{-7}$,
 $\kappa = 7.20 \times 10^{-2}$;

$$(10), U = 13 \text{ cm/s}, h_{\infty} = 0.4 \text{ cm}, \lambda = 6.61 \times 10^{-5},$$

$$K = 9.22 \times 10^{-2};$$

$$(11), h_{\infty} = 0.4 \text{ cm}, L = 3000 \text{ cm}, \lambda = 1.65 \times 10^{-5},$$

$$K = 2.30 \times 10^{-2}; \text{ and}$$

$$(12), h_{\infty} = 0.1 \text{ cm}, L = 750 \text{ cm}, \lambda = 1.03 \times 10^{-6},$$

$$K = 2.88 \times 10^{-3}.$$

(44)

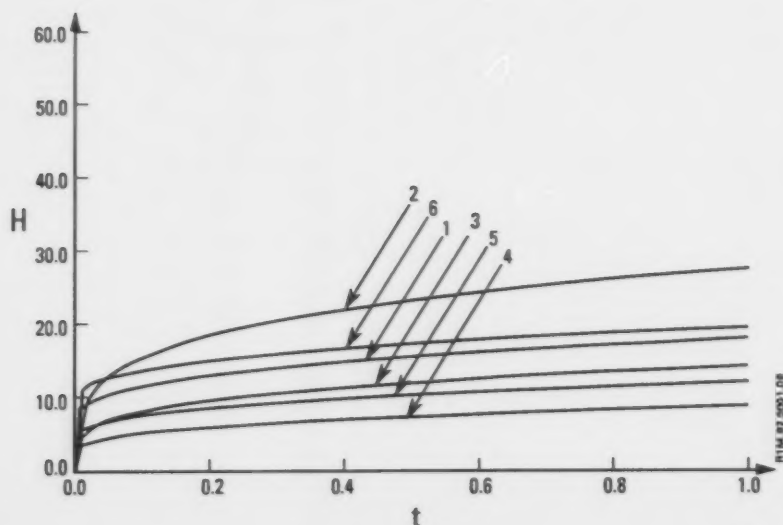


Figure 5. The dimensionless oil-layer thickness H as a function of the nondimensional spatial coordinate t , for the cases of Eq. 43.

Figure 7 presents the corresponding results for $H(t)$ for most of the cases of Eq. 44. The rather well-defined front of the towed-boom-thickened region, and the oil thickness at the boom (often several centimeters for a millimeter-thick oil film), are noteworthy. Because the length of the boom-thickened oil layer L is typically 1.5 m or more, the maximum compressional-strain rate for $u_1(x)$ is $O(1/s)$. Figure 8, which identifies the location in (K, λ) space of the dozen cases just enumerated, suggests the dimensionless-parameter ranges of particular physical interest.

It is worth noting that for some combinations of parameter values, the numerical results suggest that the operation may be unsatisfactory, because the operation is ineffective and/or unstable

[e.g., $H(t)$ barely exceeds unity at $t = 1$ and/or $w(t)$ goes to zero for $t < 1$ and/or highly oscillatory behavior of $H(t)$ or $w(t)$ occurs].

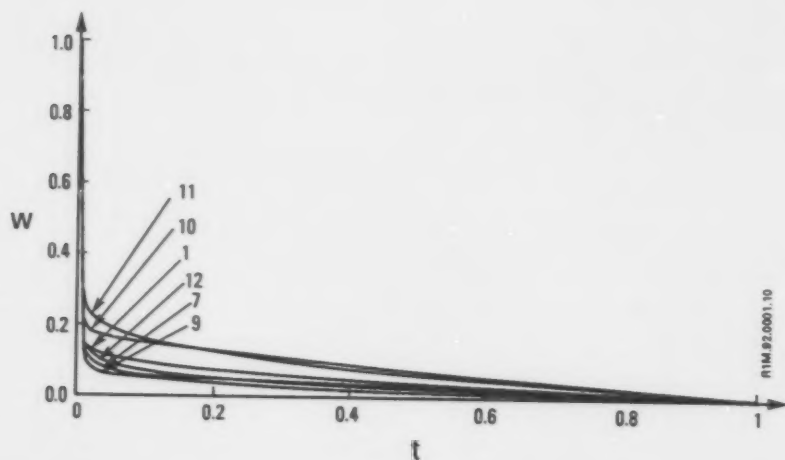


Figure 6. Same as Fig. 4, but for most of the cases of Eq. 44.

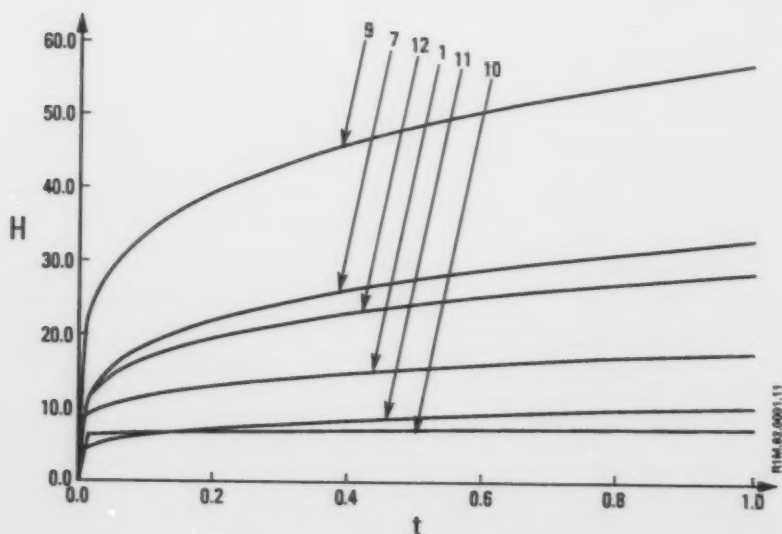


Figure 7. Same as Fig. 5, but for most of the cases of Eq. 44.

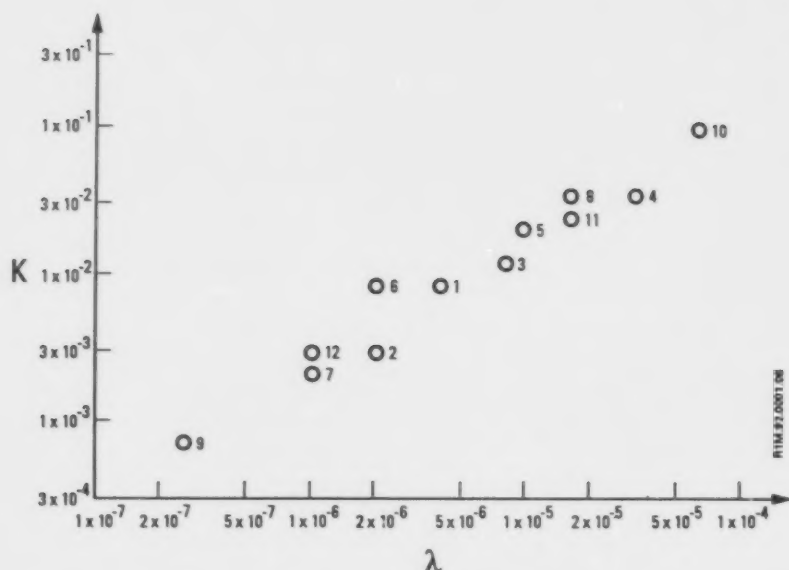


Figure 8. Identification in (K, λ) space of the twelve illustrative cases specified by Eqs. 41-44. The combinations of dimensionless parameters which comprise the dimensionless groups K and λ are defined in Eq. 30.

BOOM CONFIGURATION

To this point, we have carried out a one-dimensional analysis of an oil-herding-and-burning operation, taken to be quasisteady in the frame of reference fixed in the (towed) boom. Here we examine more closely the configuration taken on by the boom, described above simply as U-shaped. We model the boom as a uniform flexible string, which supports no compression or shearing stress or bending moment, so that the force exerted at any point in the string can be only a tension T directed along the tangent to the string at that point (Figs. 9 and 10) [19]. The distance s^* is the arc length measured along the string from the point of symmetry (taken to be the origin of a Cartesian coordinate system fixed in the boom: $x^* = y^* = 0$). The super asterisk is present to distinguish the present usage of some conventional symbols from our earlier usage of the same symbols for other designations. The towing is taken to be such that the y^* axis is an axis of symmetry.

If D denotes the fluid-dynamic drag on the towed boom owing to the flow U , then the balance of forces locally normal to the boom gives (C_D , the drag coefficient, is approximately unity for the range of the Reynolds number of practical interest [20], H^* is depth of the wetted part of the boom):

$$T d\theta = D ds^* = (\rho/2) C_D (U \cos \theta)^2 H^* ds^* ; \quad (45)$$

$$\frac{d\theta}{ds^*} = \frac{\rho C_D U^2 H^*}{2T} \cos^2 \theta, \text{ so } \tan \theta = k s^* \quad (46)$$

by symmetry, provided that T is a constant and

$$k \equiv \rho C_D U^2 H^* / (2T) .$$

However, dT/ds^* is equal to the drag locally tangential to the string, and, since this drag is negligible, T is indeed constant. If L^* is half the length of the boom, then

$$\tan \theta_0 = k L^* , \quad (47)$$

where ρ , C_D , U^2 , H^* , and L^* are taken as known. While the tension T is not taken as given, the towing vessels must continue to pull in a fixed direction θ_0 to keep the boom configuration unchanged in time.

Since $(dy^*/dx^*) = \tan \theta$ and $(ds^*)^2 = (dx^*)^2 + (dy^*)^2$,

$$\frac{dx^*}{ds^*} = \cos \theta = (1 + k^2 s^{*2})^{-1/2} ,$$

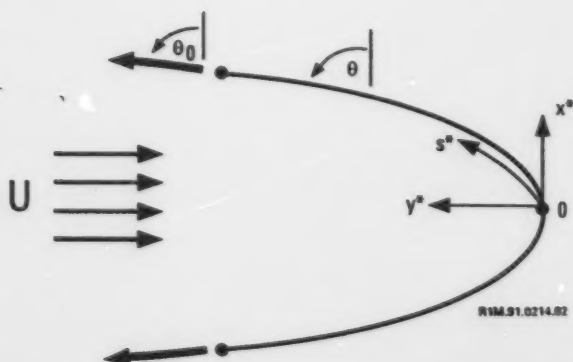


Figure 9. Sketch of the coordinate systems used in examining the boom configuration for herding and burning an oil film on water.

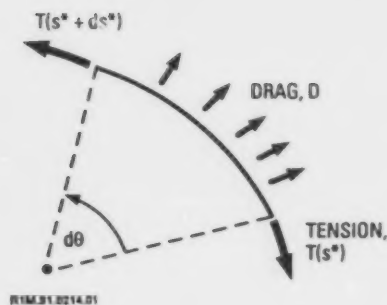


Figure 10. Sketch of the force balance used in examining the boom configuration for herding and burning an oil film on water.

$$\frac{dy^*}{ds^*} = \sin \theta = ks^* / (1 + k^2 s^{*2})^{1/2}. \quad (48)$$

Hence, with $L^* \geq s \geq 0$,

$$\begin{aligned} x^*(s^*) &= k^{-1} \ln[ks^* + (1 + k^2 s^{*2})^{1/2}], \\ y^*(s^*) &= k^{-1} [(1 + k^2 s^{*2})^{1/2} - 1]. \end{aligned} \quad (49)$$

From Eqs. (47) and (49),

$$\begin{aligned} x^*(L^*) &= \frac{L^*}{\tan \theta_0} \ln(\tan \theta_0 + \sec \theta_0), \\ y^*(L^*) &= \frac{L^*}{\tan \theta_0} (\sec \theta_0 - 1). \end{aligned} \quad (50)$$

For $[(\pi/2) - \theta_0] \equiv \epsilon$, where $0 < \epsilon \ll 1$, i.e., for the case in which the two craft tow slightly divergently from a parallel alignment, $x^*(L^*) \approx L^* \epsilon \ln(2/\epsilon)$ and $y^*(L^*) \approx L^* - O(\epsilon L^*)$. More generally, from Eq. 50, for assigned θ_0 and L^* , the separation distance $x^*(L^*)$ is inferred; alternatively, for assigned $x^*(L^*)$ and L^* , the towing angle θ_0 is inferred. The parameter k follows from Eq. 47, so the entire boom configuration follows from the parametric representation of Eq. 49. Numerical examples are provided in Fig. 11.

REMARKS ON THE ANALYSIS

The model treated here adopts the Oseen approximation, does not pursue the details of flow stagnation at the boom, and takes the oil layer to remain coherent. We believe that we have solved the model to the accuracy warranted. In general, pursuing more meticulous

mathematical solution of the above formulation does not seem appropriate without first inquiring into the magnitude of possible modifications owing to turbulent transition; standing waves established by the presence of the towing vessels and the boom; pre-existing waves, currents, and/or winds; and firespread rate. Further work on the containment configuration may consider a model of the boom beyond that of the string idealization adopted here.

One exception to this recommendation concerns the fact that a solution is furnished above for a two-dimensional problem: a one-dimensional or two-dimensional problem often is usefully considered at the outset of almost any combustion-front-propagation investigation. Extension to a three-dimensional description of oil-layer depth during a remediation operation might be usefully undertaken with just the phenomena currently included in the model.

PERTINENT LABORATORY EXPERIMENTS

The experiments to be discussed may all be carried out in a flume, a (modestly) sloped channel into which one can introduce water, a surface layer of oil, and (if desired) a stationary boom past which the liquid may flow (Fig. 12). The capacity to have a finite wind speed w may be noted. Of course, the inlet and outlet may be plugged so that tests without a moving layer are encompassed.

The first, crucial laboratory experiments are those that delineate the amount of burning oil consumed per unit area per time, i.e., the quantity m , with the units of a speed. The data for m should be sought for types of oils of interest and for oil-layer depths of interest, with wind speeds of interest and with extension to oil/water emulsions to simulate some of the consequences of "weathering" [21,22] of spilled oil. While the existence of appreciable data from burning oil films over water sublayers in pools of various data has been noted in the introduction, the desired information cited here appears to go beyond what is available.

The next set of laboratory experiments is transient tests of the flame-propagation speed across the water-supported oil film, for a range of interesting values of each of the above-listed parameters.

If the results continue to support the practicality of the scheme, currently plausible on the basis of a quite limited number of uninstrumented trials at sea, then the next step would be to try to simulate the entire phenomenon in the laboratory; it is this encompassing simulation that is depicted in Fig. 12. Such an inclusive laboratory simulation would entail a moving layer, ignition at time zero, and spread of flame across the oil layer.

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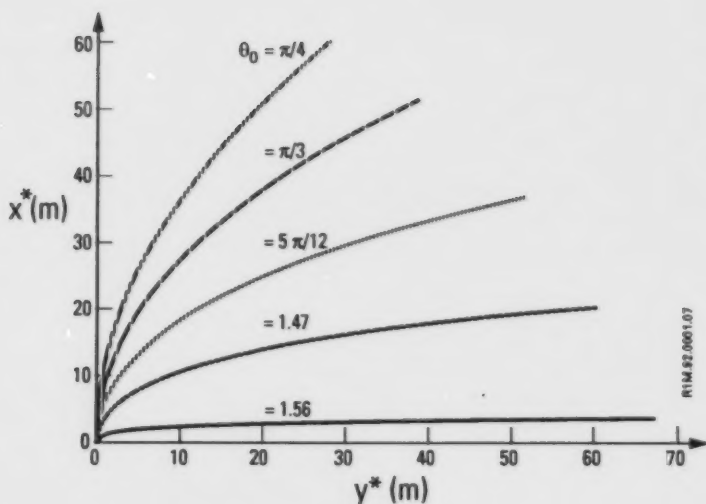
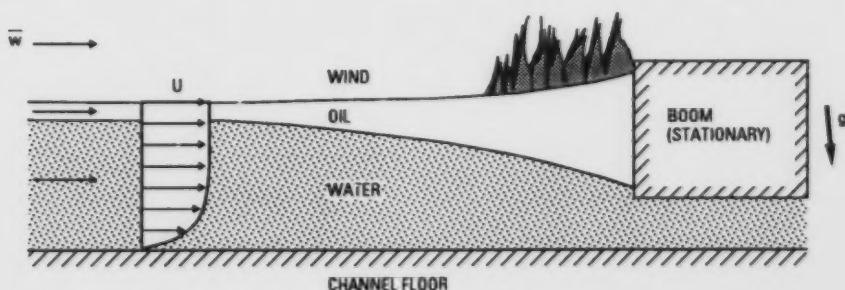


Figure 11. The configuration of half the boom, in terms of the coordinate system introduced in Fig. 8, from Eqs. 47 and 49, for a half-boom length $L^* = 67.5$ m and for various tow angles θ_0 . The full boom configuration is implied since the configuration is symmetric about the y^* axis.



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Figure 12. Schematic of a flow-through experiment in a (slightly inclined) channel with a stationary boom, and a burning oil layer at the surface of the water. The wind speed is w and the liquid phases move at speed U far from the boom (aside from boundary layers); however, after a fetch, the wind alters the liquid speed from U , as does the approach to the boom.

NOMENCLATURE

C_D	coefficient of drag, defined in Eq. 45
D	drag, [N]
$d(x)$	magnitude of the depth of the oil-water interface below the level of the ambient water surface, [m]
$f(s)$	$M(x)/(Uh_w)$
g	magnitude of the gravitational acceleration, [m/s ²]
$H(s)$	$[\eta(x) + d(x)]/h_w$
H^*	depth of the wetted part of the boom, [m]
h_w	ambient thickness of the oil slick, [m]
K	dimensionless parameter defined in Eq. 30
$K(s)$	integrably singular kernel defined above Eq. 36
k	$\rho C_D U^2 H^*/(2T)$, [1/m]
L	magnitude of the value of the x coordinate at which the oil-layer thickness begins to vary from h_w , [m]
L^*	half the length of the boom, [m]
$M(x)$	$\int_x^0 \dot{m}(\delta) d\delta$, [m ² /s]
$\dot{m}$	oil-surface-regression rate, [m/s]
$p(x,y)$	pressure, with datum at the air-oil interface, [Pa]
s	x/L
s^*	distance along the arc of the boom (Fig. 9), [m]
T	tension along the tangent to the boom, [kg/(m s ²)]
t	$s + 1$
U	towing speed, [m/s]
$u(x,y)$	component of velocity in the x direction, [m/s]
$u_1(x)$	$u[x, -d(x)]$, [m/s]
$u^*(x,y)$	$u(x,y) - U$, [m/s]
$v(x,y)$	component of velocity in the y direction, [m/s]

$w(s)$	$u_1(x)/U$
x	horizontal Cartesian coordinate, with origin at the boom, [m]
x^*	Cartesian coordinate defined in Fig. 9, [m]
y	vertical Cartesian coordinate, with origin at the ambient water surface, [m]
y^*	Cartesian coordinate defined in Fig. 9, [m]
ϵ	$(\pi/2) - \theta_0$
ζ	Fourier-transform variable, [1/m]
$\eta(x)$	height of the air-oil interface above the ambient water surface, [m]
θ	angle defined in Fig. 9
θ_0	asymptotic value of θ , holding at the end of the boom (Fig. 9)
λ	dimensionless parameter defined in Eq. 30
μ	viscosity of the water, [kg/(m s)]
μ_0	dynamic viscosity of the oil, [kg/(m s)]
ν	μ/ρ , [m ² /s]
ρ	density of the water, [kg/m ³]
σ	density of the oil, [kg/m ³]
$\tau_{xy}(x,y)$	component of the shear-stress tensor, [kg/(m s ²)]
Superscript	
-	Fourier-transformed quantity

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SMOKE REDUCTION FROM POOL FIRES USING FERROCENE
AND DERIVATIVES

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INTRODUCTION

In previous publications (Mitchell, 1990, 1991 a,b) it has been reported that the compound ferrocene (dicyclopentadienyl iron) is very effective in reducing smoke emissions from crude oil fires. It is believed, therefore, that the use of such additives will be beneficial in making the In-Situ combustion of oil spills more environmentally acceptable. A number of other applications involving large pool fires can also benefit from the use of smoke reducing chemicals. This paper will describe some recent studies that have been made to investigate the efficacy of ferrocene derivatives in reducing smoke emissions from crude oil and a number of other hydrocarbon fuels.

FERROCENE DERIVATIVES

A series of acyl and alkyl substituted ferrocene derivatives have been synthesized in the laboratories of ESSO Resources and at the University of Western Ontario and laboratory scale burn tests have been performed to determine their relative smoke reducing efficiencies. In these tests, a 10 ml of oil/additive mixture is burned in a crucible and the smoke, arising from the combustion, is drawn through a fibreglass filter by means of a vacuum pump. The soot, collected on the filter and on the filter holder is scraped off and its volume measured¹. The tests are usually repeated three times to yield a consistent average soot volume.

A list of the compounds studied is given in Table I and figure 1 is bargraph showing the relative smoke yields from using these compounds, at a concentration of 2% by weight, in Norman Wells Crude Oil. Figure 2 shows a similar bargraph for the same additives used at 0.2% concentration.

¹Because of the small soot masses collected and the high temperatures that the filter is subjected to, it has been found that measuring the soot volume gives results that are much more consistent than soot mass measurements.

#	Additive	Formula	FW	m.p.	b.p.
1	Ferrocene	$(C_5H_5)_2Fe$	186	174	249
2	Butyl	$(C_4H_9)(C_5H_4)Fe(C_5H_5)$	242	L	183
4	Pentyl	$(C_5H_{11})(C_5H_4)Fe(C_5H_5)$	256	L	90
5	Butyryl	$(C_3H_7CO)(C_5H_4)Fe(C_5H_5)$	256	L	144
6	Valeroyl	$(C_4H_9CO)(C_5H_4)Fe(C_5H_5)$	270		92
7	Iso-Valeroyl	$(C_4H_9CO)(C_5H_4)Fe(C_5H_5)$	270		150
8	Dimethyl	$(CH_3)_2Fe(C_5H_4)_2$	216		
9	Trimethyl Acetyl	$(CH_3)_3Fe(C_5H_4)(C_5H_3)$	230		
10	Hexanoyl	$(C_5H_{11}CO)(C_5H_4)Fe(C_5H_5)$	284	L	161
11	Heptanoyl	$(C_6H_{13}CO)(C_5H_4)Fe(C_5H_5)$	298	L	84
12	Octanoyl	$(C_7H_{15}CO)(C_5H_4)Fe(C_5H_5)$	312		
13	Oct/Dioctanoyl	$10\%[(C_7H_{15}CO)_2(C_5H_4)_2Fe]$	325	L	
14	Decanoyl	$(C_9H_{19}CO)(C_5H_4)Fe(C_5H_5)$	340		203
15	Lauroyl	$(C_{11}H_{23}CO)(C_5H_4)Fe(C_5H_5)$	368	36	
16	Myristoyl	$(C_{13}H_{27}CO)(C_5H_4)Fe(C_5H_5)$	396		
17	Palmitoyl	$(C_{15}H_{31}CO)(C_5H_4)Fe(C_5H_5)$	424	59	
18	Stearoyl	$(C_{17}H_{35}CO)(C_5H_4)Fe(C_5H_5)$	452		

It can be seen that as the molecular weight increases, the effectiveness of a given additive decreases when added at a fixed weight concentration. Since iron, however, is the active smoke reducing agent, increasing the molecular weight means that, for a given additive, the percentage of iron is reduced. Normalizing the smoke yields to the percentage of iron used shows that the variation between the additives is much less and indeed for the 0.2% case, the efficiency per iron atom is constant.

Also shown in figures 1 and 2 is the soot yield normalized to the molecular weight of ferrocene. It can be

seen that the heavier derivatives are much less effective on a per weight basis than ferrocene. The multiply substituted compounds, however, appear to be more effective than ferrocene.

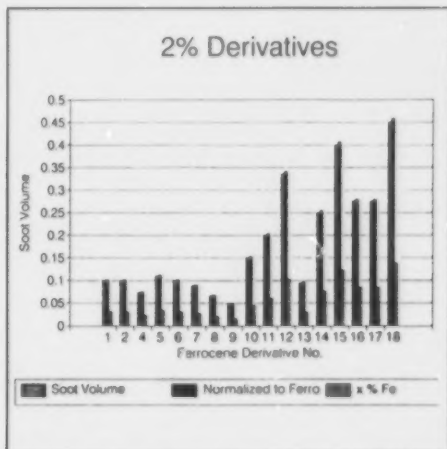


Figure 1. Relative soot volume for the additives listed in Table I, used at 2% concentration.

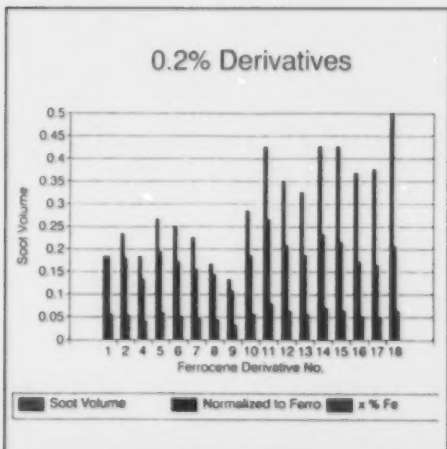


Figure 2. Relative soot volumes for the additives listed in Table I used at 0.2% concentration.

EFFECTIVENESS OF FERROCENE FOR OTHER FUELS

During the course of this project, series of burn tests were performed at London Municipal Airport in which ferrocene was premixed with JETB fuel at varying concentrations. Although the volume of fuel used in these fires was moderate (102 gallons/fire), their areal extent was large since the fuel was poured directly onto the ground. The estimated fire dimensions were about 50' in diameter. It was found that the soot yields from these fires was larger than expected even when the additive was used in a concentration of 2%. This unexpected result prompted a series of laboratory scale burn tests in which several different fuels were burned, with and without ferrocene addition. Again soot yields were measured using the technique described above. The results are quite surprising and are shown in figure 3.

Particularly noticeable is the very large soot yield from the gasoline fuel. Even using ferrocene, the smoke yield exceeds that for untreated Norman Wells crude oil!

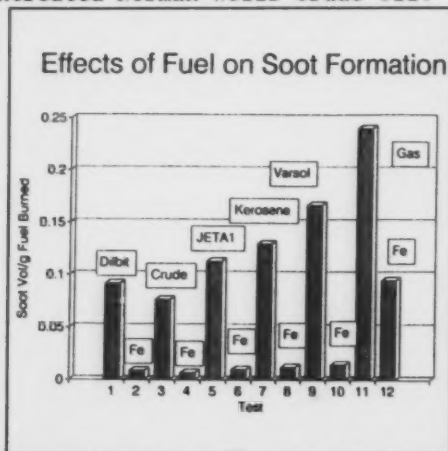


Figure 3 Relative soot yields for various fuels with and without ferrocene addition.

Work is continuing to find an additive that will be more effective than ferrocene in reducing smoke yields for light fuels such as gasoline or JETB. A series of intermediate-size test burns is scheduled to be performed at the National Fire Laboratory in Ottawa in which this additive will be tested and the emissions arising from the combustion of such light-fuel/additive mixtures will be analyzed.

MESO-SCALE TESTING OF SMOKE REDUCTION FROM DILBIT COMBUSTION

As mentioned in earlier reports, ferrocene, while being very effective in reducing smoke emissions from crude oil fires, is not suitable for use in oil spills for it is a solid compound which is more dense than water. In addition it is not very soluble in oil. The information gathered from this research program has allowed us to develop a new additive which is in liquid form and which can be sprayed directly onto the oil surface. This additive, designated RMS 9757 may be scheduled for production by ESSO Chemicals Ltd.

A test of this additive was performed at the Calgary Fire Training Centre in March. Dilbit was used as the fuel and this was floated on top of water in an 8' x 8' burn pan. Figures 5 and 6 show the fires from untreated and treated Dilbit and it can be seen that a dramatic reduction in smoke yield was found in the latter case. This was very encouraging for it was the first trial of an additive directly sprayed onto the fuel.

ON OCEAN TESTING

An In-Situ Burn Test has been planned for the Beaufort Sea of the coast of Northern Alaska for August, 1992. This is sponsored by the US Coast Guard and co-ordinated by Alaska Clean Seas. We have been asked to participate in this test and plan to perform a burn test in which the additive RMS 9757 will be sprayed onto 100 bbls of North Slope Crude Oil contained inside a 3M Fire Boom, prior to combustion. Air sampling equipment mounted on surface vessels and on an aircraft belonging to the University of Washington will be used to analyze the emissions arising from this burn test.

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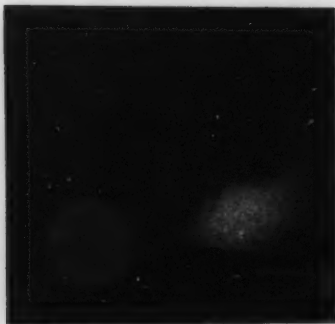


Figure 4. Burn test using untreated Dilbit on water. (8' x 8' Burn Pan).

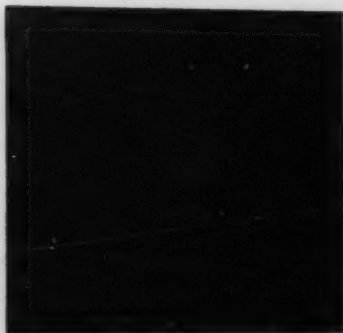


Figure 5. Burn test using treated Dilbit on water.

Laboratory Evaluation of Biodegradation of Crude Oil Contaminated Tundra Soil

by

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SUMMARY

Review of the literature found that bioremediation techniques have good potential for accelerating the microbial degradation of petroleum hydrocarbon in tundra soils. Previous studies and case histories have shown that hydrocarbon-degrading organisms are ubiquitous in the Arctic and spilled oil does degrade in tundra soils and pond sediments. However, without enhancement, oil degradation may be slow and the contamination can persist for long periods. In contrast, nutrient enhancement form fertilization can significantly increase the degradation rates of crude oil. Aerating the soil by tilling may further accelerate this process.

Techniques for optimizing the microbial degradation of hydrocarbons still need development, however. Of particular interest is whether aerobic or anaerobic degradation should be promoted in tundra soils. To help address this question, a laboratory experiment was designed to evaluate oil degradation rates in heavily contaminated soil samples from the 2U site under various redox and nutrient conditions. In addition, the use of oil-degrading bacteria were evaluated.

In the laboratory experiment, reduction of total petroleum hydrocarbons (TPHs) by indigenous bacteria was found to be negligible under aerobic conditions for all nutrient amendments over a period of 12 weeks. The unexpectedly poor performance of the aerobic treatment may have been due to the high concentration of hydrocarbons (153,487 ppm) and the slow rate at which the indigenous bacteria grew, or the preferential use of biogenic carbon over petroleum hydrocarbons. In contrast, under anaerobic conditions TPH was reduced by 47% in the high nitrogen and phosphorous microcosms. The unexpectedly good performance of anaerobic bacteria indicates that promotion of oil degradation in saturated subsurface soils is feasible. The best degradation rates, however, were achieved by application of bacterial amendments, which reduced TPH up to 60% over 12 weeks. The higher degradation rates using bacterial amendments were attributed to the relatively rapid rate at which the bacteria colonized the substrates. This result suggests that bacterial additions in the field would be useful for promoting more rapid degradation of oil, while the slower growing indigenous oil-degrading bacteria population is allowed to increase.

INTRODUCTION

The complex interactions between prokaryotes and eukaryotes is marked in the Arctic environment. Thus, the impact by Arctic oil and gas exploration and procurement since the 1970's has interrupted processes which are limited to the few months when temperatures allow the tundra's surface to thaw. Persistence is a major problem confronting the fate of petroleum hydrocarbons in Arctic tundra soils contaminated by oil spills. Numerous studies have been conducted to document the role of microbial degradation of these petroleum hydrocarbons, indicating that many natural populations of oil-degrading aerobic and anaerobic bacteria exist (Atlas, 1984a, 1985; Linkens *et al.*, 1984). Isolates from various sites include the bacterial genera *Achromobacter*, *Acinetobacter*, *Alcaligenes*, *Arthrobacter*, *Brevibacterium*, *Cytophaga*, *Flavobacterium*, *Pseudomonas*, *Spirillum*, and *Xanthomonas* (Cook and Westlake, 1974; Cundell and Traxler, 1974).

Knowledge of *in situ* rates and the nature of hydrocarbon degradation in cold soils is limited. Experimental oil-release studies have generally found long persistence times of hydrocarbon contaminants and slow rates of microbial degradation. A study of the long term fate of oil-contaminated soils at Norman Wells and Tuktoyaktuk showed that 30-50% of surface oil and 40-60% of subsurface oil remained 7 and 8 years after the spills (Mackay, 1984).

The recovery of tundra vegetation after oil-spill damage is related to physical, chemical, and biological properties. An assessment of the damage from the 1989 oil spill near drill site 2-U in Kuparuk Oilfield, Alaska, was extrapolated from physico-chemical data collected from similar soils (Dames and Moore, 1986; Jorgenson, 1989). Thaw depths at the 2-U site in September 1989 ranged from 13 to 19 cm (except below the valve, which reached 28 cm) and organic layer depths ranged from 3 to 9 cm. Based on similar soils, the organic layer can be expected to have an organic carbon content of 20-50% and a volumetric moisture in the saturated subsurface of 60-90%. The soil can be expected to be slightly alkaline (pH 7.5-8.0), high in total nitrogen (N) (0.2-0.6%) and phosphorous (P) (0.1-0.6%), but low in available ammonium nitrogen (NH_4 , <1-5 ppm), nitrate nitrogen (NO_3) (1-10 ppm), and phosphate (<1 ppm). Exchangeable cations are relatively high, particularly calcium (3000-9000 ppm).

The shallow active layer and saturated soil conditions present a range of aerobic and anaerobic conditions. Water ponded on the soil surface can be expected to be anoxic, and anaerobic bacteria will predominate. However, on better drained soils of moist tundra encountered on the upper slope of the spill site, the surface (0-5 cm) is unsaturated, highly porous, and open to relatively rapid diffusion of oxygen to support aerobic metabolism. The subsurface remains saturated by the suprapermafrost groundwater, leading to anaerobic activity. Since most of the oil is restricted to the surface, the promotion of aerobic metabolism of the petroleum hydrocarbons is most feasible.

There are several additional factors which may affect the biodegradation of petroleum hydrocarbon-contaminated soils. The high organic carbon contents will have a large but uncertain affect on the biodegradation of petroleum hydrocarbons. Organic material can adsorb hydrophobic organic solutes, reducing their mobility and enhancing their presentation to microbes. They provide an alternative carbon source to microbes, but the denitrifying process may remove the assimilable material prior to targeting the contaminants (Paul and Clark, 1988; Mihelic and Luthy, 1988 a,b). They may also promote cometabolic activities, especially when there is a mix of soil microorganisms and organic compounds (Glaser *et al.*, 1989). Soil organic carbon increases the rate of denitrification by serving as an electron donor (Reddy, 1982; Paul and Clark, 1988).

In this study, we report on how oxygen availability, redox potential, and specific bacterial populations control biodegradation of hydrocarbons in crude oil contaminated tundra soils. Treatment and maintenance of hydrocarbon-contaminated tundra soil under various redox, nutrient, and bacterial amendment regimes were analyzed over a 14 week period. We monitored changes in total petroleum hydrocarbons (TPH) and hydrocarbon constituents, and determined microbial densities in the acclimated and amended microcosms.

MATERIALS AND METHODS

Soil Handling and Preparation

Bulk samples of heavily contaminated tundra soil were obtained from the 2U site on 15 June 1990. The samples were kept frozen at ABR's office in Fairbanks until shipped to Waste Stream Technology's (WST's) laboratory in Buffalo, NY. Material was shipped frozen, in approximately ten, 2 kg aliquots in plastic freezer storage bags. Preservatives were not added to samples prior to shipment. Samples were sent via UPS and arrived within three days from the time of sample acquisition, arriving intact, at <32°F. The experiment was initiated on 18 July 1990. The soil was prepared in cooled deionized water amended with contaminated soil after pooling into a batch. All samples were handled using the precautions listed by OSHA Standards, Hazard Communications Standard CFR 1910.1200.

Culture Conditions and Amendments

The pooled soil preparation was aliquoted to flasks. Each prepared microcosm sample consisted of 500 gm of soil at field capacity plus 1%. All treatments were performed in duplicate. Sealed, 1000 ml flasks (BBL Microbiology GasPak System, Becton Dickinson and Co., Cockeysville, MD) were used for all anaerobic samples. Open, 1000 ml narrow-mouthed (9 cm) glass flasks were used for all aerobic samples. Temperature was maintained at 10°C (48°F) in a sealed, refrigerated incubator throughout the study.

The studies were designed to compare the activity of indigenous biodegradation rates using three levels of nutrient availability, within two redox conditions, and biodegradation rates within soils amended with bacteria (Waste

Stream Bioblends) using one level of nutrient availability within one redox condition. Aerobic microcosms were stirred for approximately 30 seconds, twice daily, while nutrients were added every other day. Microcosms were amended with a Mineral Medium consisting of (in mg/L): $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 33.4; FeCl_3 , 0.25; K_2HPO_4 , 21.75; KH_2PO_4 , 8.5, with a resultant pH of approximately 6.8. In addition, the following nutrient amendments were made:

- (1) Low nitrogen (0.1 g/L $(\text{NH}_4)_2\text{SO}_4$) and high phosphorous (1.0 g/L Na_2HPO_4) (DEC N, INC P).
- (2) High nitrogen (2.0 g/L $(\text{NH}_4)_2\text{SO}_4$) and low phosphorous (0.05 g/L Na_2HPO_4) (INC N, DEC P).
- (3) High nitrogen (2.0 g/L $(\text{NH}_4)_2\text{SO}_4$) and high phosphorous (1.0 g/L Na_2HPO_4) (INC N, INC P).
- (4) High nitrogen (2.0 g/L $(\text{NH}_4)_2\text{SO}_4$) and high phosphorous (4.3 g/L KH_2PO_4 , 12.9 g/L K_2HPO_4), and bacterial amendments using WST Bioblends.

Anaerobic microcosms were amended with NaNO_3 at a final concentration of 1 mM (150 mg/L) at time zero and at each sampling period. Nitrate will serve as the final electron acceptor (versus oxygen). Similarly, anaerobic microcosms were stirred for approximately 30 seconds, twice daily, and immediately recharged with fresh GasPaks (BBL) to maintain anaerobic environments.

Aerobic microcosms specifically amended with proprietary bacteria, WST Bioblends, bacteria with demonstrated hydrocarbon utilizing capabilities, were inoculated, on average, with approximately 5×10^5 bacteria/gram soil twice weekly. The bacteria are cultures isolated by Waste Stream Technology Inc., maintained on nutrient agar plates and stored lyophilized at -70°C . Cultures used to amend various microcosms included *Pseudomonas putida* (M-5), *Pseudomonas fluorescens* (P-JBH), and *Psychrobacter* sp. (P-NH). Colonies from plates were used to aseptically inoculate 1000-ml Erlenmeyer flasks containing 500 ml of mineral media supplemented with sodium citrate (0.2% w/v). The flasks were incubated for 48 h at 10°C while mixing with a magnetic stir bar.

Bacterial enumeration was performed according to procedures outlined in the Standard Methods for the Examination of Water and Wastewater, method SM-907. Briefly, one gram of the soil was eluted in 10 ml Mineral Medium for 10 minutes. From this stock solution, various 10-fold dilutions were plated onto nutrient agar plates. In addition, the three most prominent bacteria were typed at least three intervals throughout the study. They were speciated using the Biolog Microstation System (Biolog, Inc., Hayward, CA).

Physical and Chemical Analyses

Analytic evaluations for Total Petroleum Hydrocarbons (TPH) were performed for each sample at the initiation of the study (time zero) and after 2, 4, 6 and 14 weeks. Total Petroleum Hydrocarbons (TPH) were analyzed as follows: Soil samples were extracted for non-volatile organic compounds using EPA Method 3550 (EPA SW-846, 1986). Briefly, 2 gm of soil (composited from a minimum of six areas) is mixed with anhydrous sodium sulfate and solvent extracted using sonication. The dried extract is concentrated, and put in a compatible solvent, Gensolv D (1,1,2-trichlorotrifluoroethane). EPA Method 418.1 (Kopp and McKee, 1983) was used to analyze the TPH via infrared spectro-photometry, using a Perkin-Elmer model 1310 dispersive infrared spectrophotometer, fixed or variable wavelength, with a scan range of 4000 to 600 cm^{-1} wavenumbers. The percent transmittance is used to compute the absorbance, which determines the TPH level in parts per million (ppm). This analytical program takes into account dilution factors, solid percentages (using dry weights) and a slope factor, which is predetermined through initial calibration of the IR. In calculating the slope factor, five initial calibration standards of various concentrations are analyzed on the IR forming a linear graph, from which the slope factor is calculated.

Major oil components (alkanes, aromatics, asphaltenes, and NSO's) were analyzed following soil sample extraction for organic compounds using EPA Method 3550. A Hewlett-Packard model 5890 series II gas chromatograph (GC) with split/splitless injector and jet separator for packed column analysis, model 5970 mass selective detector, model 7376A autosampler, and HP-Unix Chemstation for the complete operation of the GC/MS, measured the aromatics using EPA Method 8020. The other petroleum fractions were quantitated using the Standard Method for Boiling Range Distribution of Petroleum Fractions by Gas Chromatography, ASTM D 2887-84 (modified 8015), using a Perkin-Elmer model 8500 gas chromatograph (GC) with dual packed column injectors, equipped with a Tekmar model LSC 2000 purge and trap concentrator, Tekmar model ALS 2016 16 place autosampler, and Perkin-Elmer model 2600 PC integrator. Briefly, the total peak area of the scan compared with the calibration scan converts them to $\mu\text{g/ml}$. This number multiplied by the extraction volume (10 ml), divided by the amount of soil extracted (approx. 10 gm), was divided by the dilution of extracted soil. The resultant value divided by the fraction of solids determines the final concentration of contaminants, in ppm.

The Redox potential of each treatment was monitored at each sampling interval. This was measured with an Orion model 9678BN combination redox electrode (Orion Research, Inc., Boston, MA), which was inserted in the flask.

Using the LaMotte soil test system (LaMotte Chemical Products Co., Chestertown, MD), soil texture, pH, and micro- and macronutrient profiles were determined.

Statistical Analyses

Statistical significance of TPH measurements was assessed using the coefficient of determination, r^2 . Significance of measurements of TPH was compared within the groups, between the groups, as well as with an untreated control, to determine the mean effect of oxygen and various nutrients as they relate to microbial degradation of TPHs.

RESULTS

Initial Soil Characteristics

Approximately 100 gm of pooled soil was dried overnight in an oven at 100°C, and extracted with Gensolv D. This procedure was used prior to nutrient and pH analyses due to the high amount of the petroleum hydrocarbon contaminant, and also provided material for a GC hydrocarbon scan of the contaminant (modified 8015 analysis). The extracted soil was slightly acid (pH 6.4) and calciferous (7000 ppm) and contained adequate amounts of inorganic nutrients known to support microbiological activity. The following micro- and macronutrients were present (in ppm): P, 200; NO₃, 10; NO₂, 2.0; NH₃, 10.0; K, 220; SO₄, >2000; Mg, 20.0; Mn, 14.0; Fe, 15.0; Cu, 10.0; Cl >500; and Al, 10.0. The soil was 100% silt, comprised of decaying plant matter coated with crude petroleum.

The 418.1 TPH analysis of the pooled soil sample resulted from multiple grabs of a composite sample totaling 2 gm per extraction. This was performed with two samples plus a duplicate, resulting in an average of 153,487 ppm TPH (on a dry weight basis). In addition, the modified 8015 hydrocarbon profile of two, 10 gm composited samples revealed an average of 265,999 ppm TPH (on a dry weight basis). These analyses revealed that the distribution of the contaminant in the soil lacked uniformity. The 8270 analysis of a composited sample and a duplicate revealed that there were virtually no polynuclear aromatic hydrocarbons present in the samples (less than the detection limit of 2.5 ppm). The initial redox potential in all of the microcosms was approximately +100 mV.

Composite samples were obtained from each of the individual microcosms and the average number of colony forming units (CFU) per gram of soil was determined. The initial average was approximately 5×10^7 CFU/gm soil.

Petroleum Hydrocarbon Concentrations

Aerobic Microcosms

Each microcosm was sampled after 2 weeks, 4 weeks, 6 weeks, and 14 weeks of treatment. Summarized in Table 1 are the 418.1 TPH analyses (in ppm) for individual microcosms, the average of the duplicates, and the percent reduction compared with the initial, average TPH. The TPH (in ppm) for each microcosm, and the average of the duplicate microcosms, are also presented in Figures 1-4.

Table 1. TPH concentrations (ppm, EPA Method 418.1) in microcosms at five periods during treatment.

Microcosm	Day 0	Day 14	Day 28	Day 38	Day 42	Day 84	Percent Change
CONTROL							
HgCl ₂ (A) aerobic		208233	76752	136949	99648	99674	-35
HgCl ₂ (B) aerobic	153487	86774	88378	90277	72828	61071	-60
HgCl ₂ (C) anaerobic	153487	119762			86505	54525	-64
dH ₂ O (A)		68789	83267		92635	101656	-34
dH ₂ O (B)	153487	166960	111454		96733	94339	-39
AEROBIC AMENDED							
PNH (A)		37716	74889		76199	80045	-48
PNH (B)	153487	126394	96929		105326	103792	-32
P-JBH (A)		96198	86442		85811	90293	-41
P-JBH (B)	153487	89349	73665		81780	62385	-59
M-5 (A)		58589	54359		49229	72448	-53
M-5 (B)	153487	91647	85252		82722	51925	-66
AEROBIC							
INC N INC P (A)		133575	168181		154798	177375	+16
INC N INC P (B)	153487	72426	83501		83877	86974	-43
DEC N INC P (A)		78453	98013		82894	94392	-39
DEC N INC P (B)	153487	160113	170207		173998	185682	+21
INC N DEC P (A)		75137	60213		103252	200846	+31
INC N DEC P (B)	153487	138315	109612		112931	89040	-42
ANAEROBIC							
INC N INC P (A)		113331	74479		71637	79465	-48
INC N INC P (B)	153487	136229	75935		97703	83666	-45
DEC N INC P (A)		46727	81603		83481	80049	-48
DEC N INC P (B)	153487	135109	136206		176717	99612	-35
INC N DEC P (A)		142114	84880		118388	119999	-22
INC N DEC P (B)	153487	101362	85234		90668	90421	-41

Duplicate microcosms, (A) and (B)

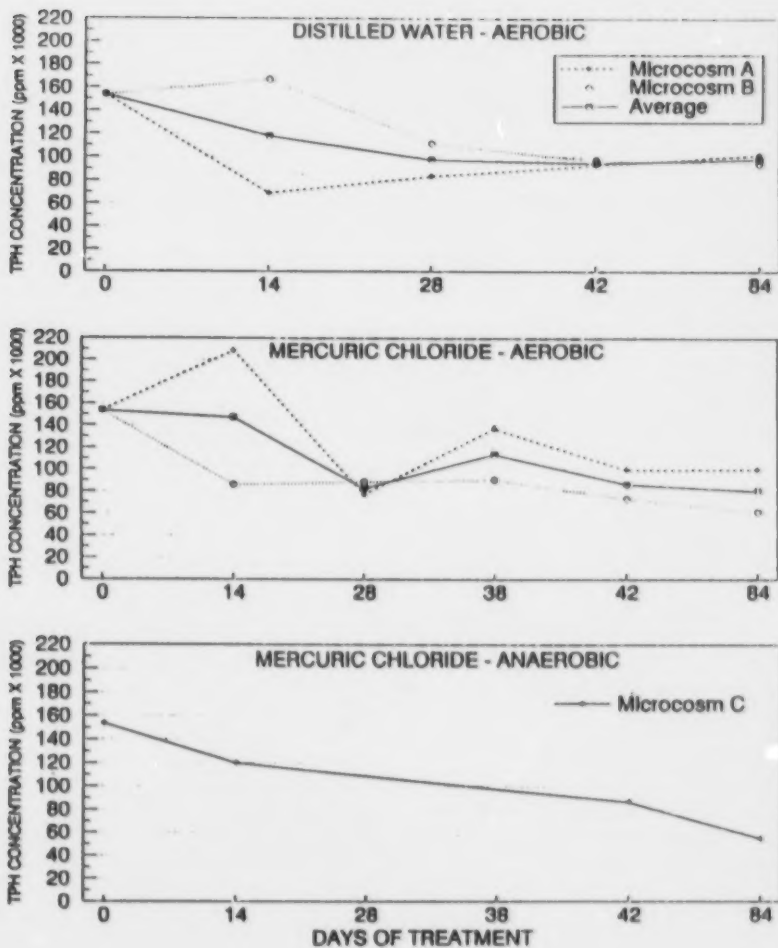


Figure 1. TPH concentrations in aerobic and anaerobic control microcosms.

The most dramatic reduction in TPH occurred in the bacterially (WST Bioblend) amended microcosms (Figure 2). The rate of degradation in these microcosms was the most pronounced during the first 14 days of treatment; culture M-5 reduced the TPH by 51% (to 75,118 ppm), culture P-NH reduced the TPH by 46.5% (to 82,055 ppm), and culture P-JBH reduced the TPH by 39.6% (to 92,774 ppm). The reduction of TPH in the bacterially amended microcosms tapered off during the remainder of the treatment period. By day 84, the TPH levels continued to decrease in the M-5 microcosms to an average of 59.5% (to 62,187 ppm), and in the P-JBH microcosms to an average of 50.3% (to 76,339 ppm).

In comparison, the TPH levels decreased in the distilled water control microcosms to an average of only 36.1% (to 97,998 ppm) (Figure 2). Although there appeared to be a significant decline in TPH in all of the nutrient amended soils by day 28, by day 84 there was a maximum reduction of 13.9% (to 132,175 ppm) in the INC N, INC P microcosms (Figure 3).

All of the microcosms demonstrated marked variability within the treatment modality and between different treatments, and at different time points. This is illustrated in Figures 1-3. The most heterogeneity is seen with the day 14 samples, especially in the nutrient amended microcosms (Figure 3). In general, the patterns recorded over time are consistent within individual microcosms throughout the 84 day study period.

The coefficient of determination (r^2) measured the linear correlation of the TPH analyses for each microcosm as compared with the distilled water (control) treated microcosms. These are presented in Table 2.

The hydrocarbon scan (modified 8015) analyses of various microcosms were performed after 14 weeks of treatment. The microcosms chosen for these analyses were based on their performance determined by the 418.1 analyses. In contrast to the 418.1 IR analyses, the initial and final TPH concentrations were substantially different. The 8015 analyses performed on the initial pooled soil and day 84 samples are presented in Table 3. The percent reduction of TPH were calculated using the initial TPH determined by the 8015 analyses, as well as the initial 418.1 analyses. The former evaluations lead to a greater percent reduction in TPH, while the latter result in reductions that are comparable with (or somewhat greater than) those observed with the day 84, 418.1 analyses. This holds true for all samples evaluated except for the INC N, INC P microcosms, which showed a 67.8% decrease (to 48,531 ppm) via 8015, versus a 13.9% decrease (to 132,175 ppm) via the 418.1 procedure.

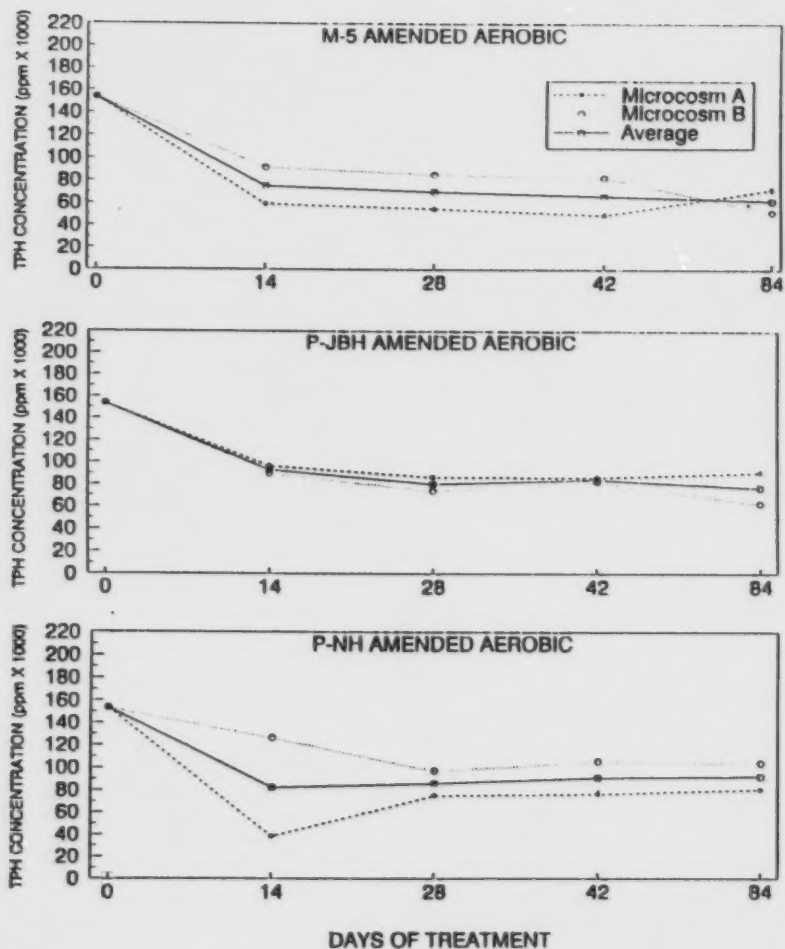


Figure 2. TPH concentrations in aerobic microcosms amended with bacteria.

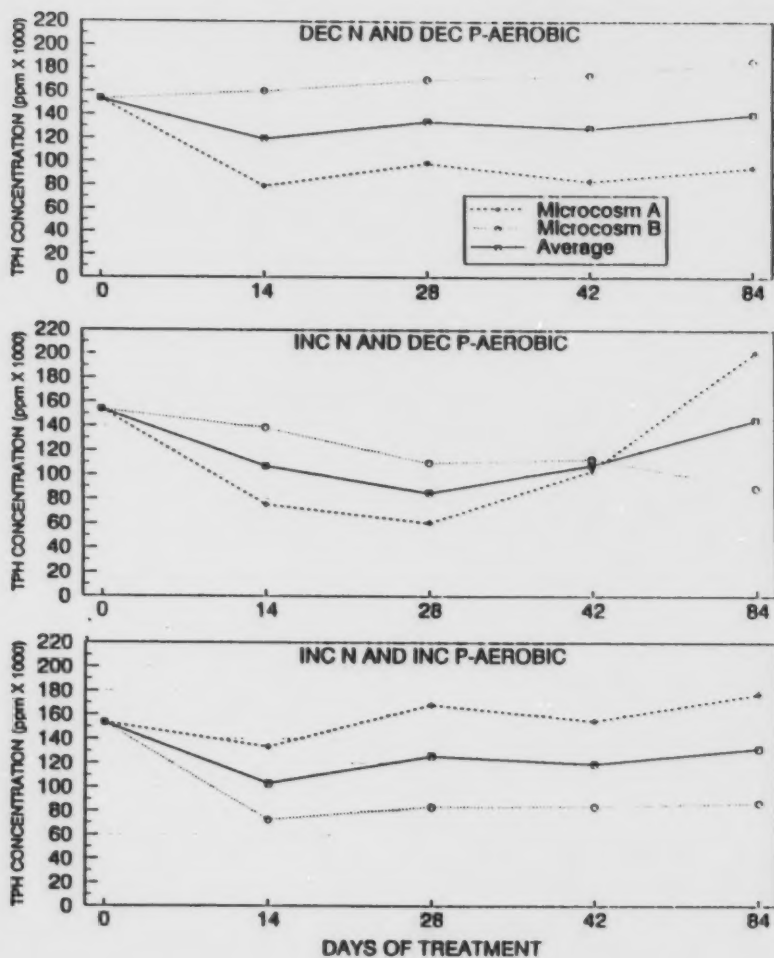


Figure 3. TPH concentrations in aerobic microcosms with indigenous bacteria.

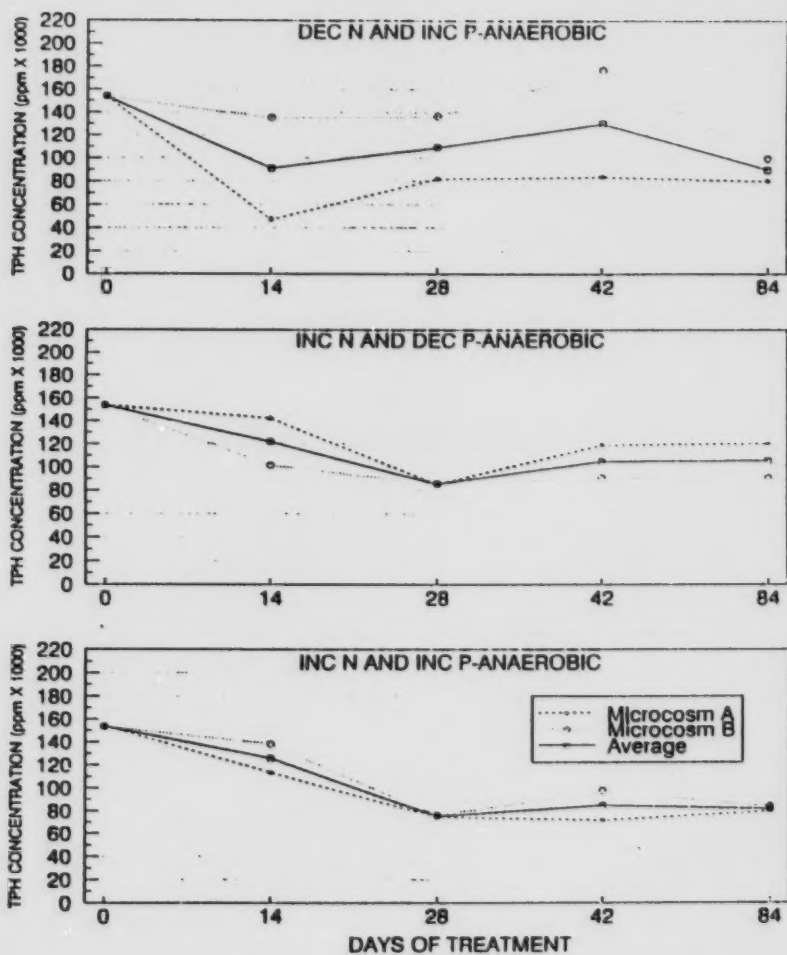


Figure 4. TPH concentrations in anaerobic microcosms.

Table 2. Regression analyses for aerobic and anaerobic microcosms.

Microcosm	r ²
CONTROL	
HgCl ₂	.77
AEROBIC BACTERIA AMENDMENTS	
M-5	.92
P-JBH	.94
P-NH	.77
AEROBIC	
INC N, INC P	.32
DEC N, INC P	.33
INC N, DEC P	.35
ANAEROBIC	
INC N, INC P	.93
DEC N, INC P	.40
INC N, DEC P	.84

Table 3. TPH concentrations (ppm, modified EPA Method 8015) in microcosms at the beginning and end of treatment.

Microcosm	Day 0	Day 84	Percent Change
CONTROL			
HgCl ₂ aerobic (A)			
HgCl ₂ aerobic (B)	237,508	108,480	-54
dH ₂ O (A)			
dH ₂ O (B)	237,508	94,620	-60
AEROBIC AMENDED			
PNH (A)			
PNH (B)	237,508	43,584	-82
P-JBH (A)			
P-JBH (B)	237,508	56,748	-76
M-5 (A)			
M-5 (B)	237,508	37,428	-84
AEROBIC			
INC N, INC P (A)			
INC N, INC P (B)	237,508	48,532	-80
DEC N, INC P (A)			
DEC N, INC P (B)	237,508	ND	
INC N, DEC P (A)			
INC N, DEC P (B)	237,508	ND	
ANAEROBIC			
INC N, INC P (A)			
INC N, INC P (B)	237,508	81,617	-66
DEC N, INC P (A)			
DEC N, INC P (B)	237,508	ND	
INC N, DEC P (A)			
INC N, DEC P (B)	237,508	ND	

Duplicate microcosms, (A) and (B)

ND = No data

Anaerobic Microcosms

As with the aerobic microcosms, each anaerobic microcosm was sampled after 2 weeks, 4 weeks, 6 weeks, and 12 weeks of treatment. Summarized in Table 1 are the 418.1 TPH analyses for individual microcosms, the average of the duplicates, and the percent reduction compared with the initial, average TPH. The TPH (in ppm) for each microcosm, and the average of the duplicate microcosms, are also presented in Figure 4. As observed with the aerobic systems, by day 14 there appeared to be significant decreases in TPH. The reduction in the DEC N, INC P anaerobic microcosm (A) was 69.6% (to 46,727 ppm), however this was not substantiated in later samples and there was marked variability in the 418.1 analyses. The greatest decrease in TPH occurred in the INC N, INC P microcosms (an average of 46.8%, to 81,675.5 ppm). This was closely followed by the DEC N, INC P microcosms (an average of 41.5% to 89,830.5 ppm), and the INC N, DEC P microcosms (an average of 31.4% to 105,210 ppm).

The coefficient of determination (r^2) measured the linear correlation of the TPH analyses for each microcosm as compared with the mercuric chloride (control) treated microcosms. These are presented in Table 2.

The 8015 hydrocarbon scan data supported the 418.1 analyses of the anaerobic cultures (Table 3). The 8015 of the INC N, INC P microcosms determined that the TPH levels were 81,617 ppm, while the 418.1 calculated them to be 81,675.5 ppm. Thus, there was a 1:1 correlation between these two analyses.

Bacterial Concentrations

Aerobic Microcosms

Since there was no apparent growth of fungi in the original soil samples and subsequent soil samples, the number of bacteria in individual microcosms was determined at each sampling. The colony forming units (CFUs)/gm soil, at the five sampling points, are presented in Figures 5-8. There was an average number of 0.5×10^8 CFU/gm soil on day zero. At time zero, the predominant species of bacteria included *Moraxella osloensis*, *Acinetobacter* sp., *Rahnella aquatilis*, *Psychrobacter immobilis*, *Alcaligenes faecalis*, *Pseudomonas* sp., and *Pseudomonas palleronii*.

In the microcosms treated with mercuric chloride, there were few remaining bacteria by day 14. However, by day 28 the population rebounded to its original number (approximately 0.5×10^8 CFU/gm soil) (Figure 5). At this point, the soil was retreated with mercuric chloride, and at day 42 showed no signs of regrowth. Analyses on day 84 showed an approximately six-fold increase of bacteria (to 3×10^8 CFU/gm soil) compared with the initial analyses. The ability to prevent bacterial growth during the first two weeks of the study resulted in minimal TPH degradation (4% to 147,004 ppm). With the reappearance of bacteria by day 28, however, there was a concomitant reduction in TPH (46.2% to 82,565 ppm). This reduction in TPH was confirmed by the day 42 analyses (34.9% reduction to 99,926 ppm). Since these microcosms were established as controls to assess non-biological reduction of the

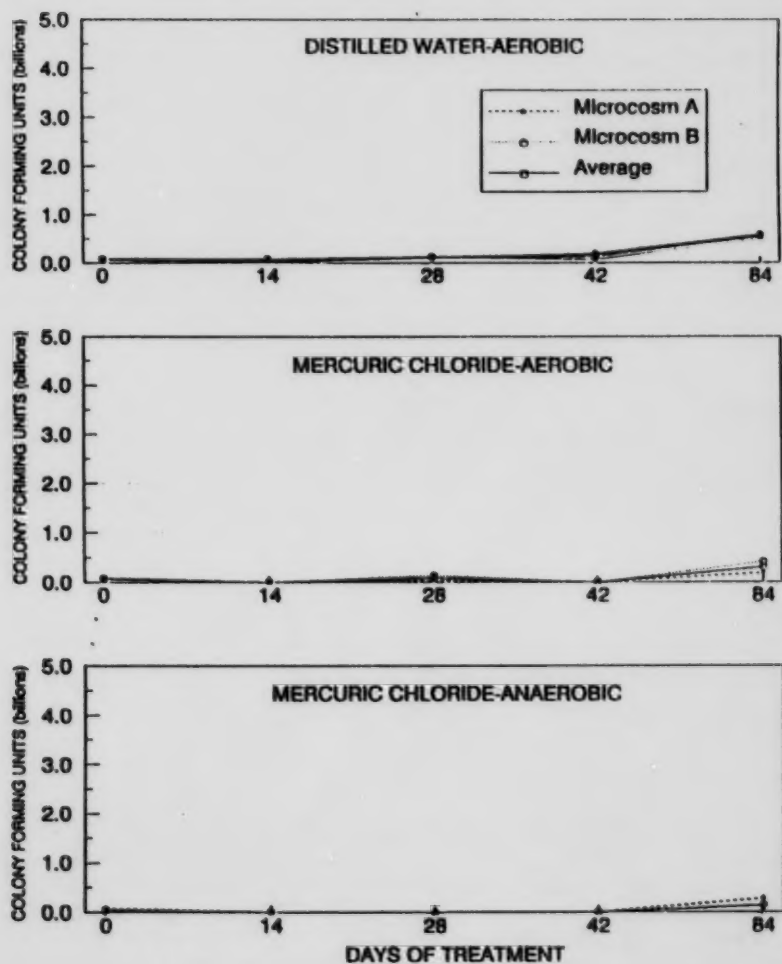


Figure 5. Bacterial concentrations in aerobic and anaerobic control microcosms.

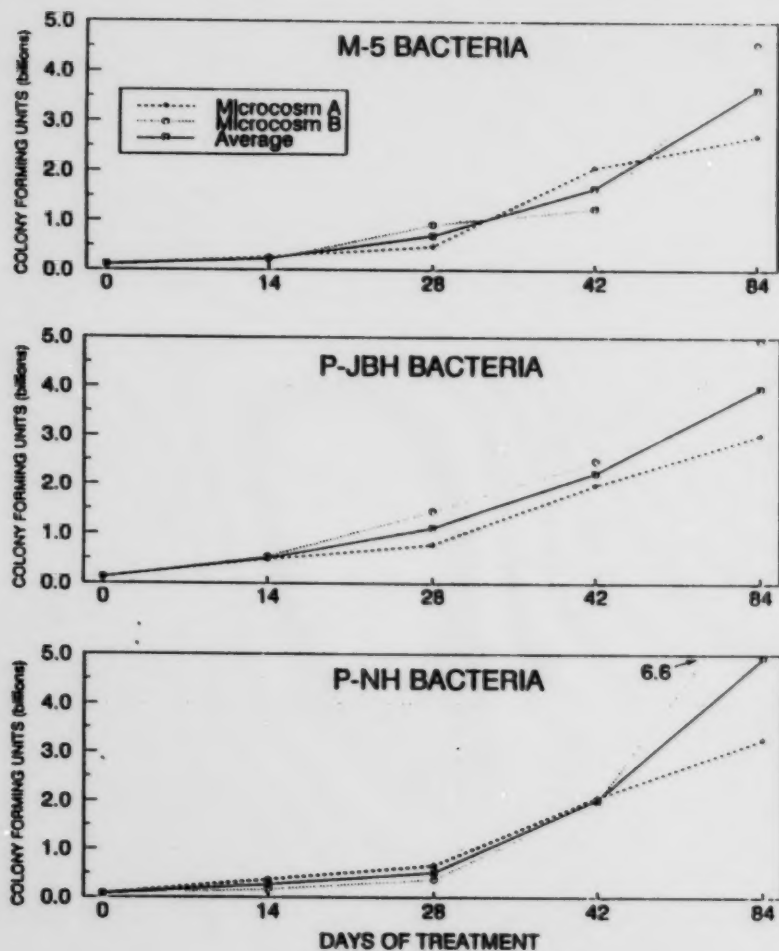


Figure 6. Bacterial concentrations in aerobic microcosms amended with bacteria.

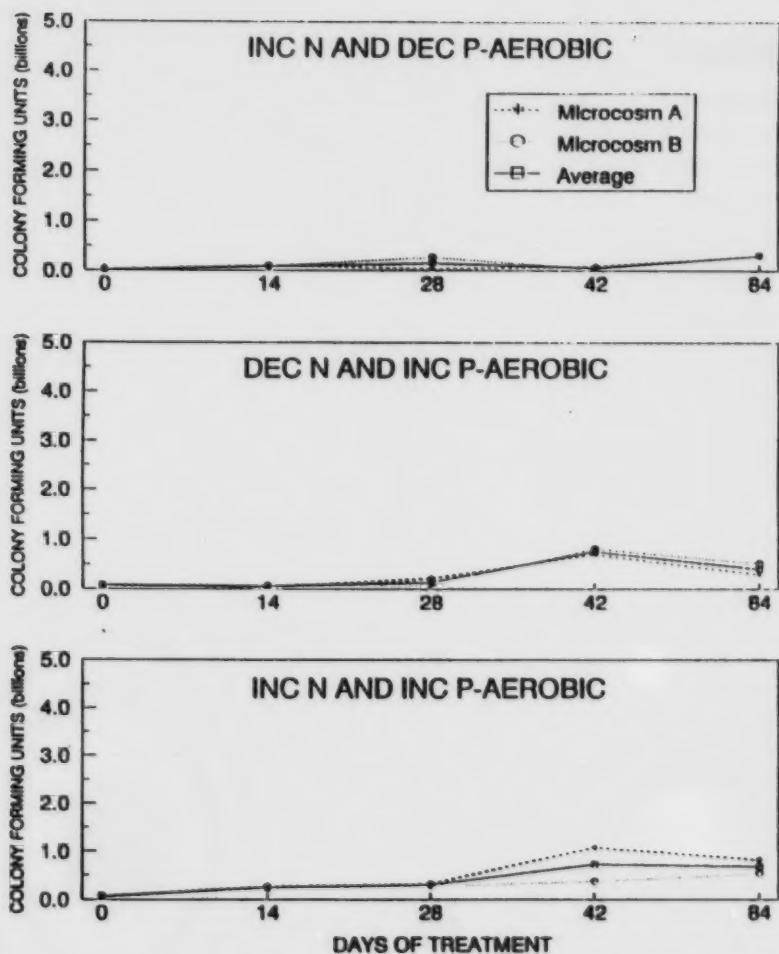


Figure 7. Bacterial concentrations in aerobic microcosms with indigenous bacteria.

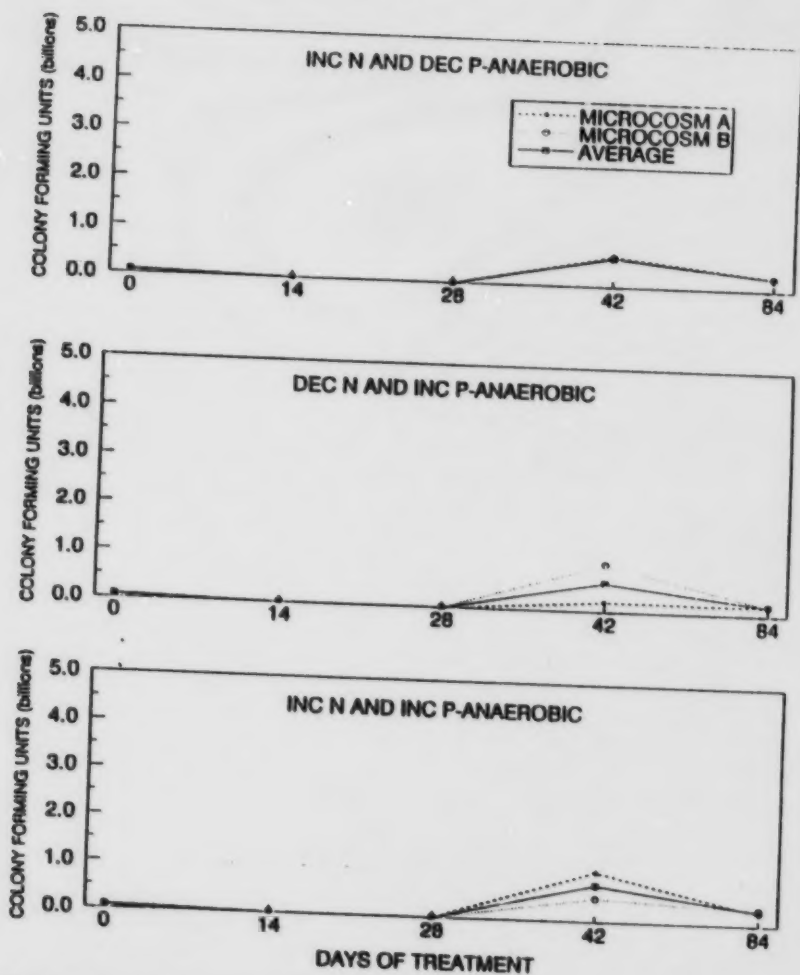


Figure 8. Bacterial concentrations in anaerobic microcosms.

contaminants, it became apparent that further treatment with mercuric chloride was moot, and the bacterial growth in these microcosms was allowed to continue through day 84.

The control microcosms which were treated with distilled water maintained their original numbers of bacteria through day 42 (approximately 10^8 CFU/gm soil), increasing five-fold by day 84 (Figure 5). This resulted in a 36.2% reduction of TPH (to 97,998 ppm) via 418.1 (Table 1), which was nearly identical to the final level of 106,392 ppm via 8015 (Table 3). The predominant species in these cultures on day 42 were *Psychrobacter immobilis*, *Alcaligenes faecalis*, and *Pseudomonas palleronii*. The predominant species in these cultures on day 84 was limited to a *Pseudomonas* sp.

Microcosms treated with the bacterial amendments demonstrated 10-fold greater numbers of bacteria than in the control microcosms (Figure 6). By day 14, there were 0.5×10^9 CFU/gm soil. The number of bacteria doubled by day 28, redoubled by day 42, and again doubled by day 84 to approximately 4×10^9 CFU/gm soil. The predominant species within these cultures was identical to the species used to amend these microcosms.

Aerobic microcosms amended with various nutrients also demonstrated continual growth, increasing ten-fold from 0.5×10^8 CFU/gm soil to approximately 5×10^8 CFU/gm soil (Figure 7). The number of CFUs/gm soil were five-fold greater than the distilled water control microcosms, but less than half those observed in the microcosms treated with the bacterial amendments. By day 84 the predominant species were *Pseudomonas palleronii*, *Pseudomonas* sp., and *Acinetobacter* sp.. The *Acinetobacter* sp. was the only organism capable of biodegrading oil when plated onto a mineral salts agar plate amended with crude oil.

Anaerobic Microcosms

The colony forming units (CFUs)/gm soil, in the anaerobic microcosms at the five sampling points, are presented in Figure 8. There was an average number of 0.7×10^8 CFU/gm soil on day zero. As observed with the aerobic microcosms treated with mercuric chloride, there was an abatement of CFUs after two weeks of treatment in the anaerobic control (Figure 5), while TPH decreased by 22% (to 119,762). The bacterial counts recovered after day 42, increasing approximately five-fold from the initial CFUs (to $>2.5 \times 10^8$ CFU/gm soil). These observations were based on a single microcosm, since the duplicate microcosm failed to maintain an anaerobic environment.

The nutrient amended microcosms showed virtually no changes until day 28 (Figure 8). By day 42 there was an increase to approximately $6-8 \times 10^8$ CFU/gm soil, which was reduced in half by day 84 (to approximately 3×10^8 CFU/gm soil). Anaerobic isolates were not speciated.

Redox Potentials

The redox potentials were determined at each sampling interval, and are presented in Figure 9. The mercuric chloride treated aerobic microcosms had a positive redox potential that increased from +100 mV to +250 mV on day 14. It remained the same through day 28, then increased to +400 mV by day 42, then decreased to +250 mV by day 84. The redox potential in the distilled water treated microcosms remained at approximately +125 mV until day 28, when it converted to a slightly negative potential (-10 mV), which remained negative through day 84. The redox potential in the anaerobic microcosm treated with mercuric chloride remained positive through day 84 (Figure 9). The maximum redox potential was reached by day 14 (+350 mV), and decreased by day 28 (+200 mV). It then increased to +275 mV and dropped to +200 mV by day 84.

The microcosms amended with the bacteria have negative redox potentials throughout the study (Figure 9). The maximum average negative redox potential of -125 mV was attained by day 28, then it grew more positive by days 42 and 84 (an average of -75 mV and -25 mV, respectively). The redox potential was greatest (the most negative) in the microcosms treated with culture M-5, reaching -175 mV by day 28.

The redox potential in the microcosms amended with nutrients steadily declined from +110 mV to approx. +60 mV (day 14), to +10 mV (day 28), until they became negative (-10 mV) by day 42 (Figure 9). The redox potential became more negative by day 84 in the microcosms with INC N, INC P and INC N, DEC P (-15 mV and -35 mV, respectively), while it became positive in the microcosm treated with DEC N, INC P (+70 mV).

The anaerobic microcosms supplemented with nutrients remained negative throughout the study period (Figure 9). By day 14, the DEC N, INC P and the INC N, DEC P nutrient amended anaerobic microcosms dropped to their maximum negative redox potential (-60 mV to -90 mV, respectively). The redox potential of the DEC N, INC P microcosms then became less negative, attaining +5 mV by day 42, and -5 mV by day 84. The redox potentials of the INC N, INC P microcosms were negative throughout the study. By day 14 and again between day 42 and 84, the INC N, INC P nutrient amended anaerobic microcosms dropped to the maximum negative redox potential (-90 mV) among anaerobic microcosms. Between these time points the redox potential was -5 mV.

DISCUSSION

In this study we demonstrated the effect of oxygen availability, redox potential, and specific bacterial populations on the biodegradation of hydrocarbons in crude oil contaminated tundra soils. The availability of petroleum hydrocarbon-degrading bacteria, nutrients, oxygen, and more highly reducing conditions, resulted in an overall decrease of 40% to 60% of initial petroleum hydrocarbon levels. This was accomplished under simulated time and temperature conditions which occur during the Arctic tundra's summer months. This study demonstrated that these events

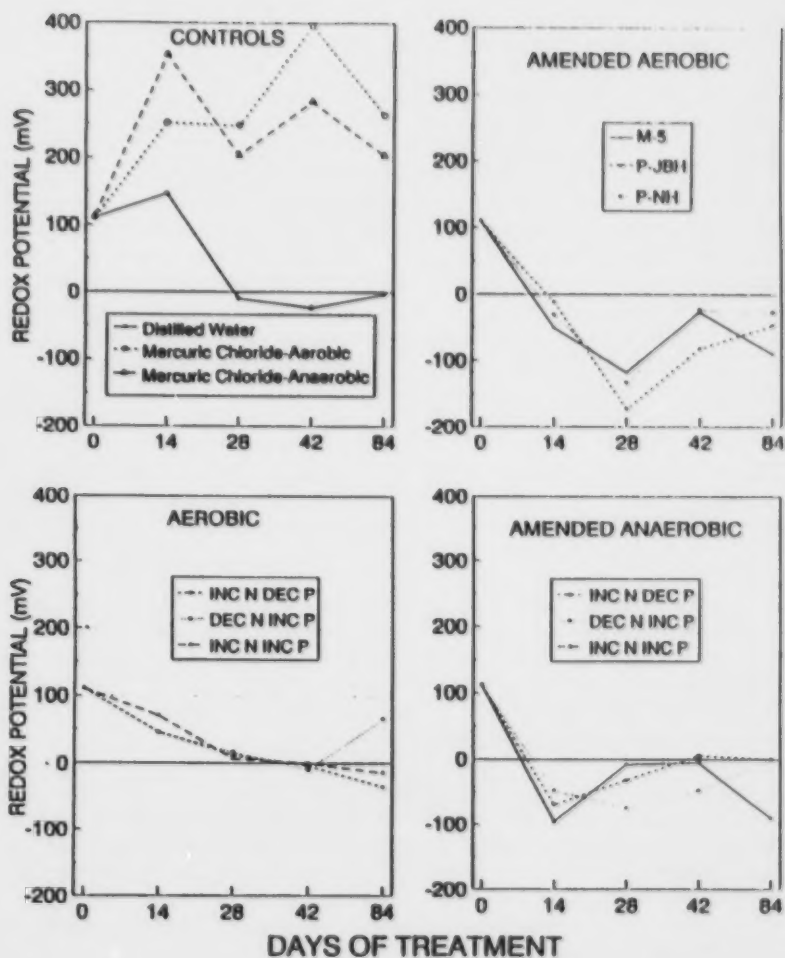


Figure 9. Redox potentials in control, amended aerobic, aerobic, and amended anaerobic microcosms.

occurred in anaerobic conditions, which are present in the flooded tundra when the warmer temperatures melt the surface ice. We also show that the rates and extent of petroleum hydrocarbon degradation are dependent on the physico-chemical nature of the contaminated soil, the extent of contamination, and the oil-degrading microbial community.

The initial analyses of micro- and macronutrients, pH, physical composition, and microbiota indicated that the soil was capable of supporting bacterial growth. The extent of contamination (at least 15%) implicated that indigenous microflora may be petroleum tolerant or petroleum degrading. The bacteria identified in the treated aerobic microcosms were less diverse than in the original soil samples, resulting in a few predominant species by day 42, and less by day 84. This indicated that there was a selection for organisms capable of surviving in these conditions. It is important to note that the levels of micro- and macronutrients in the unamended, contaminated soil were adequate for supporting bacterial growth. Further, previous research has shown that biodegradation may occur without any nutrient amendments (Atlas *et al.*, 1976; Horowitz and Atlas, 1977). The availability of nutrients in aerobic microcosms, however, was not sufficient for maximal contaminant degradation, which apparently required amendments with specific oil-degrading species. While nutrient amendments appeared to effect the extent of biodegradation of the oil in anaerobic microcosms, it is not clear if amendments with oil-degrading anaerobes would enhance the rate and extent of this activity. Based on the increased rate of initial degradation of the oil in the aerobic microcosms amended with **Waste Stream Bioblends**, similar activities may be predicted with anaerobic bacteria amendments.

No fungi grew under ideal isolation procedures (culturing on selective, enriched medias). Although high numbers of fungi have been found associated with oil spills, there are noted differences concerning their survival (Davies and Westlake, 1979), suggesting their noted absence in the samples studied (with TPH > 10%).

The enumeration and speciation of bacteria in the aerobic microcosms, and the enumeration in anaerobic microcosms, allows correlations to be made concerning biologically-mediated degradation of the oil contaminant. During the study period, we observed a ten-fold rise in bacteria in those aerobic microcosms amended with the **Waste Stream Bioblends** (compared with nutrient amended and control microcosms). The rate and amount of petroleum biodegradation by specific bacteria is well documented. For instance, over 10 tons of oil per day was biodegraded by microorganisms after the 1978 wreck of the supertanker Amoco Cadiz off the coast of France (Atlas, 1984). Although there were oil degrading bacteria present in the other aerobic microcosms (these genera are known petroleum-degraders; experiments proving their oil-degrading capabilities are in progress), more time may be required for the establishment of predominant oil-degrading bacterial species. This may be a result of competition for carbon sources, especially in this soil rich in organics other than oil (Paul and Clark, 1988; Mihelic and Luthy, 1988 a,b). The lichens may provide an easier substrate for biodegradation. Therefore, the selection pressure for oil-degrading microbes may be diminished. This would explain the lack of biodegradation by any of the indigenous microcosms. Unlike the bacterial

amendments used in our study, which are induced for petroleum biodegradation prior to inoculation, the indigenous bacteria utilize multiple carbon sources. Repeated inoculations with organisms pre-selected for hydrocarbon utilization was more successful than enhancing the indigenous microflora. Although there was evidence for anaerobic bacterial degradation, augmentation using anaerobic oil-degrading bacteria has not been assessed. Similar amendments may lead to the increased biodegradation as observed with the selected amendments.

The decreased diversity of bacteria observed in the nutrient-amended microcosms seen day 42, and more pronounced by day 84, indicated an ongoing selection for a species capable of surviving under these experimental conditions.

Statistical analysis evaluated the methodology used to measure the TPH levels in experimental versus control microcosms. The coefficient of determination, r^2 , compares the sum of squares explained (SSR) with the sum of squares total (SST). SSR is the explained variation in amended microcosms after it is related to control microcosms. SST is the unexplained variation in treatment modalities before it is related to control microcosms (in this case, distilled water amendments for aerobic microcosms, and mercuric chloride amendments for anaerobic microcosms). This can be summarized in the following equation: $r^2 = \text{SSR}/\text{SST}$; where the explained variation of samples (TPH measurements in distilled water or mercuric chloride microcosms) is compared with the total variation of samples (TPH in amended microcosms versus distilled water or mercuric chloride controls). Based on these analyses, we determined that the measurement of TPH in the aerobic microcosms amended with the **WST Bioblends M-5 and P-JBH**, compared with the distilled water control microcosms, was significant (values ≈ 1). The r^2 values for these microcosms were 0.92 and 0.94, respectively. Analysis of anaerobic microcosms determined that those treated with INC N, INC P best fit the prediction, with an r^2 value of 0.93. The INC N, DEC P microcosms had a lower r^2 value of .84, and therefore had less of a linear correlation.

The use of redox potentials as a tool to demonstrate bacterial activities was also tested. The redox potential in the initial microcosms were all positive (approximately +100 mV). We observed that an apparent correlation between a negative redox potential and subsequent oil degradation in aerobic microcosms. The microcosms exhibiting the greatest bacterial growth and TPH reduction developed the most negative redox potentials (as great as -175 mV in the **M-5** amended soils). The redox potential in distilled water treated soil eventually became slightly negative, while the other aerobic microcosms had positive redox potentials. The redox potential in the anaerobic cultures remained negative throughout the study period, concomitant with TPH reduction. In addition, the mercuric chloride control remained positive, and there was no significant TPH reduction in this microcosm. These data, together, indicate that negative redox potentials may be a predictor of biological degradation activity.

The TPH reduction, measured by the 418.1 method and verified by statistical analyses, was substantial in the aerobic microcosms amended with the **M-5** and **P-JBH** cultures. We predict, therefore, that application of these bacteria to crude oil-

contaminated tundra soil, under similar physico-chemical conditions, will lead to aerobic biodegradation of the contaminant. The TPH measurements of anaerobic microcosms supplemented with inorganic nitrogen and phosphorous indicate that the application of these nutrients to crude oil-contaminated tundra soil may lead to anaerobic biodegradation of the contaminant. The effect of amendments with anaerobic bacteria, similar to those with aerobic cultures, may prove to be a beneficial treatment modality.

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CLEANUP AND BIOREMEDIATION OF A CRUDE-OIL SPILL AT PRUDHOE BAY, ALASKA

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ABSTRACT

A crude-oil spill occurred at the S.E. Eileen exploratory well site near Prudhoe Bay, Alaska during drilling in the winter of 1969-1970. The oil infiltrated a portion of the gravel pad and flowed onto the adjacent tundra. Although some attempts were made to clean up the site at the time, a large area of contaminated gravel and tundra remained in 1990.

Based on a detailed site assessment in 1990, 2.2 ha (5.4 ac) had such high total petroleum hydrocarbon (TPH) concentrations (up to 560,000 ppm) that excavation and thermal treatment (i.e., incineration) were selected as the most appropriate remedial actions. In the remaining, less-contaminated areas that were not excavated and in subsurface soil horizons, bioremediation was selected as the most appropriate remedial action. During winter 1991, an estimated 19,000 m³ (24,860 yd³) of soil was excavated and incinerated in a 2-stage rotary kiln. During summer 1991, biodegradation of the hydrocarbons in the remaining soil was promoted by tilling, watering and dewatering (drainage), and fertilizing.

Excavation of the heavily contaminated soil reduced mean TPH concentrations by 89% at the tundra surface (from 59,013 ppm in September 1990 to 6,618 ppm in early July 1991). Bioremediation for 53 days during summer 1991 reduced mean TPH concentrations by 74% (from 6,618 to 1,698 ppm). Hydrocarbon-degrading bacteria and soil and ground-water properties important to microbial growth also were monitored.

INTRODUCTION

Crude oil was spilled at the S.E. exploratory well site during drilling in the winter of 1969-1970. The site is located in the Prudhoe Bay Oilfield, on the Arctic Coastal Plain of northern Alaska (Fig. 1). Oil infiltrated a portion of the gravel pad and flowed onto the adjacent tundra. Although some attempts were made to clean up the site at the time, a large area of contaminated gravel and tundra remained. During the intervening 20 years, the crude oil had weathered only slightly from its original state and thus required further cleanup.

The old crude-oil spill was rediscovered on 8 August 1990 by ARCO Alaska, Inc. (ARCO), when a large area of tundra north of the gravel pad and adjacent to the reserve pits was found covered by crude oil and oil-saturated gravel (Fig 2.). To clean up the site, a detailed assessment of hydrocarbon contamination at the site was performed (Jorgenson *et al.* 1991) and a remediation plan that incorporated off-site incineration of the heavily-contaminated soils and bioremediation of the remaining, less-contaminated soils was developed (Fig. 3). The site presented unique challenges for applying bioremediation techniques, because of its remote location, organic and saturated soils typical of wet tundra, and cold temperatures

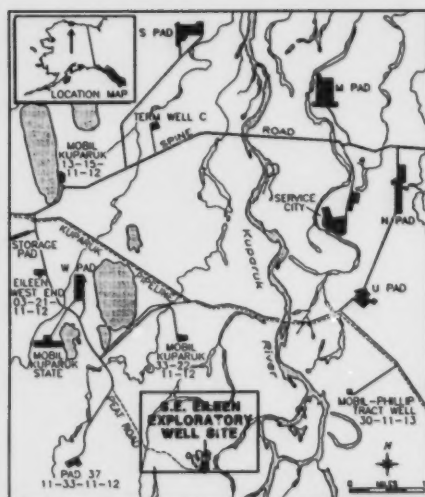


Fig. 1 Location of S.E. Eileen exploratory well site in Prudhoe Bay Oilfield, Alaska.

associated with permafrost conditions. This study presents results from the first growing season after cleanup and bioremediation began.

SITE ASSESSMENT

The site assessment described the characteristics of the terrain, delineated the areal extent and levels of contamination, and identified what hydrocarbon constituents remained. The extensive sampling program quantified total petroleum hydrocarbon (TPH; EPA Method 9071/418.1) concentrations in soil, surface water, ground water, and pond sediments.

TPH concentrations in surface and ground waters generally were very low (<1-3 ppm), although two stations within 30 m of the heavily contaminated zones were higher (11-13 ppm). These data indicated that there was little movement of hydrocarbons away from the area covered by the crude-oil spill.

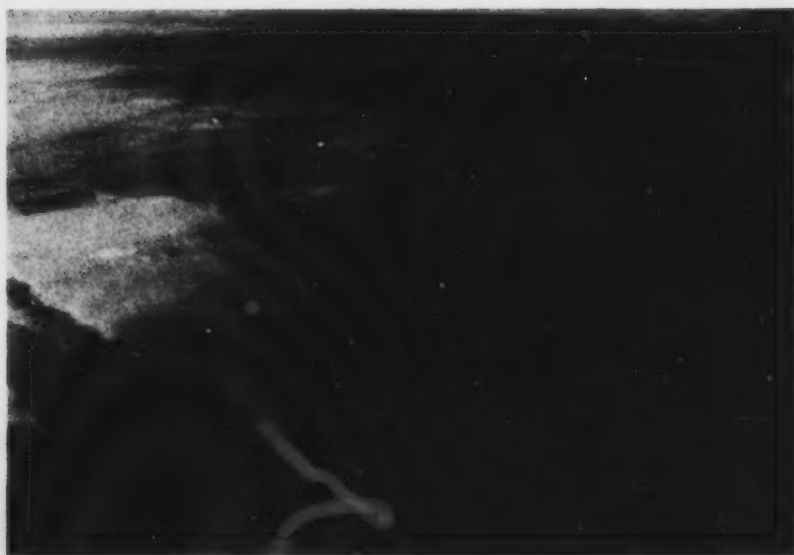


Fig 2. Aerial view of S.E. Eileen exploratory well site, Prudhoe Bay, Alaska, in September, 1990

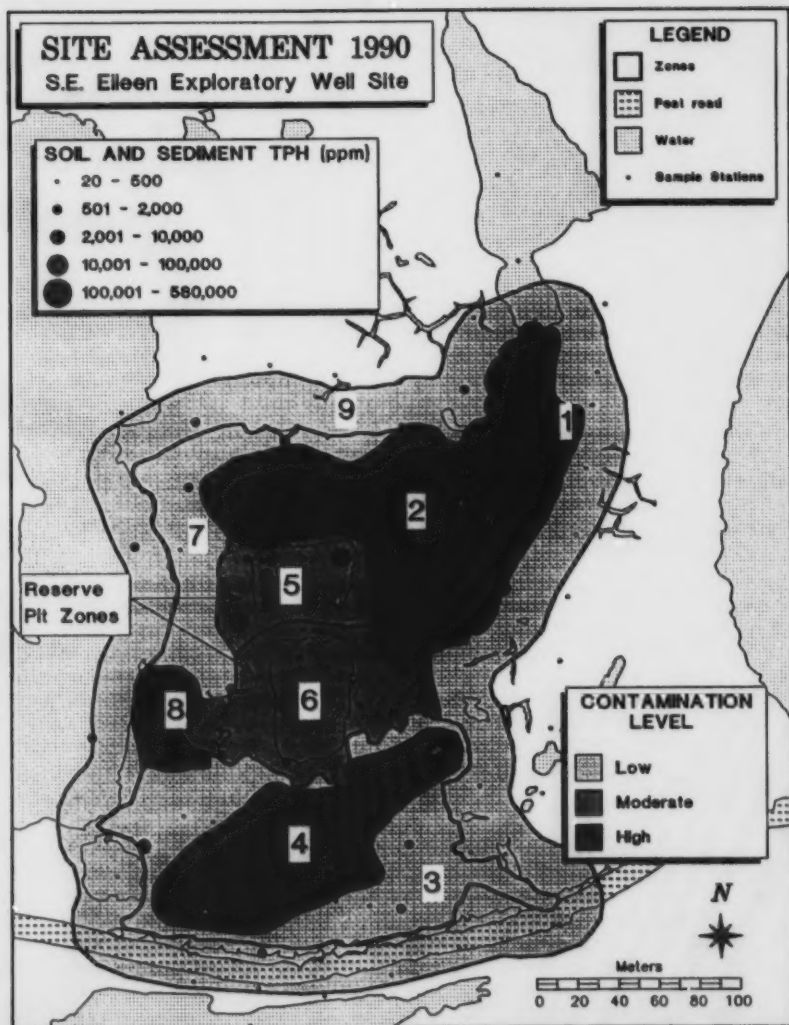


Fig. 3. Distribution of total petroleum hydrocarbon (TPH) concentrations in soils and pond sediments and remediation zones (1-9), S.E. Eileen exploratory well site, Prudhoe Bay, Alaska, September 1990. Zones 3 and 4 comprise the gravel pad. Zones 5 and 6 encompass the reserve pit areas. Total area of all zones is 7.3 ha (17.5 ac).

Soil and pond sediment sampling indicated that there was extensive hydrocarbon contamination, including diesel fuel, in and around the gravel pad, reserve pits, and the area where gravel had been placed over the original crude-oil spill. Based on characteristics of the terrain and levels of hydrocarbon contamination, the area was subdivided into nine zones for remediation treatment (Fig. 3).

Four of the remediation zones (numbers 1, 2, 4, and 8 on Fig. 3) were heavily contaminated with crude oil and/or diesel fuel. In Zone 1 (0.06 ha; 0.15 ac), the tundra was covered with crude oil. Zone 2 (1.29 ha; 3.19 ac) was a large area where crude oil had flowed onto the tundra and then was covered with a thin layer of gravel to contain the spill. Most of the oil was found in the gravel (TPH range ≤ 20 -73,000 ppm) and in the top of the active layer horizon (≤ 20 -560,000 ppm). Moderate TPH levels (120-3,000 ppm) also were found in the subsurface soil, however. Zone 4 (0.70 ha; 1.73 ac) encompassed an area of the gravel pad that was visibly contaminated with crude oil and diesel fuel. In this zone, the highest contamination (≤ 20 -100,000 ppm) was within the gravel, and lower levels (31-910 ppm) were within the underlying tundra soil. Finally, Zone 8 (0.13 ha; 0.32 ac) contained a small area of tundra and gravel that was visibly contaminated with crude oil and diesel fuel causing moderately high TPH concentrations (820-7,000 ppm) at the surface.

The two zones (numbers 5 and 6 on Fig. 3) that encompassed the reserve pits had moderate levels of contamination. In Zone 5 (0.32 ha; 0.79 ac, northern reserve pit), concentrations of both crude oil and diesel fuel were moderately high in the soil (130-33,000 ppm) and sediments (3,500-18,000 ppm). TPH concentrations in Zone 6 (0.62 ha; 1.52 ac) were low to moderate in tundra soil (150-2,200 ppm) and one sediment sample (940 ppm).

Three zones (numbers 3, 7, and 9 on Fig. 3) had low levels of contamination. Zone 3 (0.79 ha; 1.96 ac) contained the remaining clean (≤ 20 -59 ppm) portion of the gravel pad. Zone 7 (0.43 ha; 1.07 ac) was an area of tundra with a light cover of gravel; no oil was visible, but low TPH concentrations (≤ 20 -1,100 ppm) were detected in subsurface soil. Zone 9 (2.70 ha; 6.69 ac) was the large area surrounding the spill site and generally had TPH concentrations ranging from ≤ 20 ppm to 880 ppm, except at two locations (1000-2700 ppm). Moderately-high TPH concentrations also were found in sediments adjacent to the southern edge of the gravel pad (2,000 ppm) and along the shoreline at the western edge of the gravel cover (750-1,500 ppm).

WINTER CLEANUP

Four of the zones (numbers 1, 2, 4 and 8 on Fig. 3) had such high hydrocarbon concentrations that excavation and incineration were selected as the most appropriate remedial actions. The remaining portion of the gravel pad (Zone 3) also was removed to improve conditions for restoration of the tundra. From 7 to 25 April 1991, oil-contaminated soil was excavated and stockpiled for incineration by Alaska Interstate Construction (AIC). An estimated 24,860 yd³ of material was excavated and stockpiled in two piles: oily gravel and tundra soil (21,000 yd³) and clean gravel (3,860 yd³).

Excavation at the well site began with construction of an ice-road to provide access. Uncontaminated ("clean") snow then was pushed off the site, and contaminated ("dirty") snow was stockpiled within the boundaries of the contaminated area. After removal of the snow, heavily-contaminated soil was loosened by bulldozers equipped with ripping teeth, then was pushed into piles for loading into dump trucks. After the loose soil was removed, additional material from the surface and from thermokarst troughs was scraped off with a large 245 backhoe equipped with a "frost bucket". A smaller 225 backhoe equipped with a flat-bottomed bucket was

used for final scraping. Waste soil was hauled to a lined containment area on the AIC pad in Deadhorse, Alaska for temporary storage and incineration.

BIOREMEDIATION

TREATMENT

Bioremediation of the remaining, less-contaminated soils began in summer 1991. The microbial growing environment was enhanced by tilling to aerate and mix the soil, fertilizing to provide adequate nutrients, watering and dewatering (draining) to control moisture levels, and adding NO_3 (granular fertilizer) to provide an alternative electron receptor that would facilitate anaerobic metabolism in saturated subsurface soils.

Because of the organic nature of the soil (Chapin *et al.* 1980) and the 20-year acclimation period of the bacteria to the oil, indigenous bacteria were considered capable of successfully biodegrading the remaining hydrocarbons. Tilling and watering were limited to those remediation zones where soils were excavated. Two fertilizers (NPK 8-32-16 and 34-0-0) each were applied at a rate of 440 kg ha⁻¹ to all zones.

MONITORING

We monitored the effectiveness of the bioremediation treatments by determining both rates of hydrocarbon degradation and those environmental characteristics that affected those rates. Parameters were sampled at permanently marked stations and included ground-water characteristics (depth, pH, temperature, redox potential, dissolved oxygen [DO], and electrical conductivity) and nutrient levels in the soils. Densities of hydrocarbon-degrading bacteria and heterotrophic bacteria populations were determined. Sampling and laboratory analyses of soils for hydrocarbons followed standard methods (USEPA 1989).

On the basis of ground-water parameters, early summer appeared to be the most favorable period for aerobic microbial growth in the soil because ground-water levels were well below the surface, DO and redox potential were not limiting to growth, and solar radiation was greatest (Fig. 4). Conversely, anaerobic metabolism probably was favored in late summer, when the soils were saturated from rainfall and, in many cases, DO levels were below 1 ppm, indicating anoxic conditions (Fig. 4); however, aerobic metabolism can occur at DO concentrations as low as 0.2 ppm (Sims *et al.* 1989). Water temperatures usually ranged from 1 to 5°C; however, most of the oil was near the soil surface, where temperatures usually are higher. The pH of the ground water stayed within optimal pH levels (6.5-8.5) for microbial growth (Sims *et al.* 1989) throughout the summer. Redox potentials were high after snowmelt, then usually dropped to less than +50 mV until early August; generally, aerobic metabolism is favored at redox potentials greater than +50 mV (Sims *et al.* 1989). The effect of the added nitrates on redox potential is unknown, but probably helped raise it slightly. Because of dilution from meltwater, conductivity was lowest in spring, then increased to a relatively stable level.

Several strains of *Pseudomonas* bacteria probably were responsible for the decreased TPH concentrations over the first growing season (i.e., summer of 1991). Eight *Pseudomonas* strains were the most common bacteria based on a composite sample made after bacterial enumeration (Jorgenson and Cater 1992). Testing of their capacity to degrade Kuparuk crude oil showed that two *P. syringae* strains (*pv syringae* and *pv maculicola*) exhibited a good ability to biodegrade crude oil, whereas the other six strains exhibited moderate to low biodegradation abilities. The density of hydrocarbon-degrading bacteria at the soil's surface initially was unusually high (1.3×10^{-8} cfu; $n=3$), but it fell four orders of magnitude by late

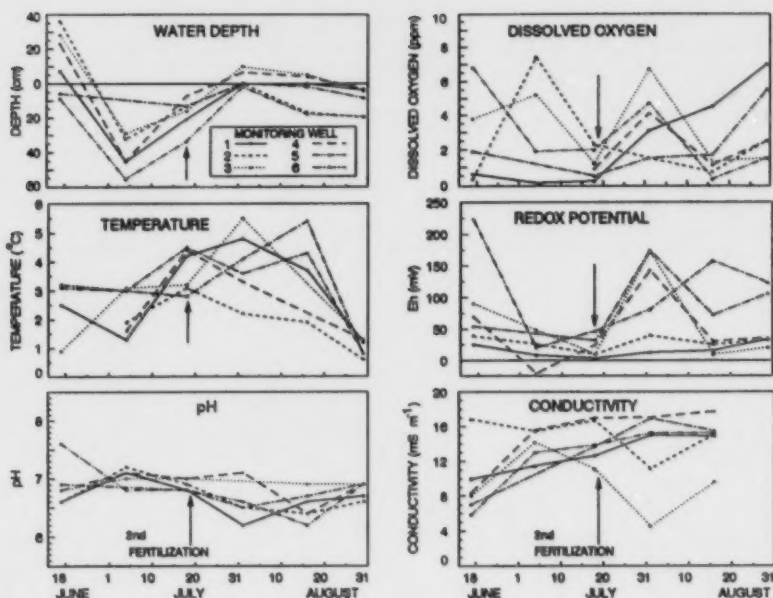


Fig 4. Bi-weekly changes in depth, temperature, pH, dissolved oxygen, redox potential, and electrical conductivity in six ground-water monitoring wells, S.E. Eileen exploratory well site, Prudhoe Bay, Alaska, 1991. Arrows indicate the date on which fertilizer was added a second time. Fertilizer was first applied on 4-5 May, 1991.

summer (9.0×10^{-4} cfu; $n=3$). Densities in surface layers were much lower than in subsurface layers and changed little during the summer. The decrease in populations of hydrocarbon-degrading bacteria in late summer probably was due to a decrease in the availability of hydrocarbons as a carbon source. Presumably, the readily-degradable hydrocarbons were used first, leaving less-degradable, compounds of heavier molecular weights.

The mean concentration of total petroleum hydrocarbons (TPH) in the active layer declined 89% between September 1990 and July 1991, primarily because of excavation of the highly-contaminated soil. From 5 July to 27 August 1991 (53 days), bioremediation resulted in a 74% reduction in the remaining TPH (Fig. 5). The reduction due to bioremediation probably was larger than that, however, because microbial activity had been occurring for almost a month before the first sampling was conducted on 5 July.

Analysis for BTEX compounds (EPA method 8020) indicated that only one station had a detectable level of benzene (0.038 ppm). Otherwise, concentrations of benzene were well below Alaska state cleanup standards (0.500 ppm). Analysis by gas chromatography (EPA method 8100m) revealed that short-chain alkanes ($< C_{10}$) already were absent from the weathered, crude-oil in the contaminated soil. In contrast, the semi-volatile, longer-chain fractions ($> C_{20}$) were abundant.

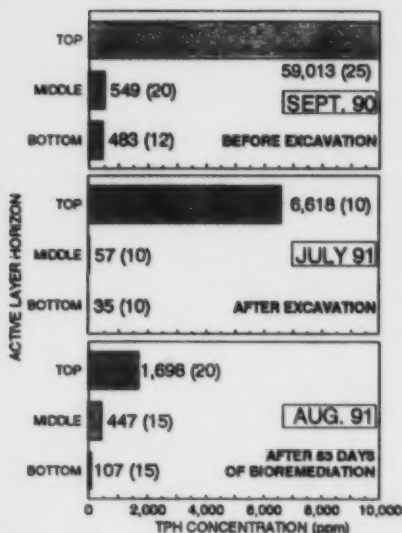


Fig. 5. Mean total petroleum hydrocarbons (TPH) in the top, middle, and bottom soil horizons of the active layer before excavation (top), after excavation and 1 month of bioremediation (middle), and 53 days after monitoring of TPH began (bottom), S.E. Eileen exploratory well site, Prudhoe Bay, Alaska. Data are means with sample size in parentheses. Six samples from uncontaminated tundra ranged in TPH from 20 to 78 ppm.

incineration may be better for small volumes. In addition, reduction of hydrocarbon levels to Alaska state cleanup standards by bioremediation may not be feasible in some situations (e.g., very high TPH levels). The cost effectiveness and limitations of bioremediation, especially under the environmental conditions in the Arctic, have yet to be fully determined.

ACKNOWLEDGMENTS

This investigation was funded by ARCO Alaska, Inc., and Exxon Company, USA. Merhadd Nadim of the Alaska Department of Environmental Conservation provided agency oversight. This manuscript was reviewed technically by Robert H. Day.

CONCLUSION

To clean up a 20-year-old spill of crude-oil in the Prudhoe Bay Oilfield, two remediation strategies were used: excavation and incineration of heavily contaminated soils and bioremediation of the remaining, less-contaminated soil. Because of the large volume and heterogeneity of the soil, neither strategy alone was sufficient to clean up the site. Excavation and incineration removed highly-contaminated soil but left less-contaminated soil. Bioremediation reduced the average remaining contamination by 74% during one growing season (53 days). On the Arctic Coastal Plain of northern Alaska, early summer appears to be the best time for aerobic microbial growth and degradation to occur. Two strains of *Pseudomonas* species showed a good ability to degrade crude oil and probably were responsible for the large reduction in TPH concentrations observed after one summer.

Bioremediation treatment initially can be much cheaper than is thermal treatment. Bioremediation monitoring may be needed over several years, however, which can increase costs greatly. Thus, cost effectiveness may depend on the volume of soil to be treated; bioremediation may be better for large volumes of soil, whereas

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**ELABORATION OF AN EXPERIMENTAL METHOD
TO ASSESS BIODEGRADATION AGENTS :
BIOREMEDIATION TRIALS ON OIL POLLUTED BEACH.**

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ABSTRACT

Many new bioremediation processes are now proposed on the market for cleaning oil polluted shores.

However the efficiency of these processes when used in open field is still controversial ; it is very difficult to distinguish between the effect of the biodegradation itself and the effect of the mechanical washing due to the waves and tides action.

CEDRE is conducting trials on a sheltered beach in Britany (France), in order to define a methodology to control and to assess these biotreatments : trials have been already conducted over a 5 months period, on 6 parcels, beforehand polluted with light crude oil and then treated by 4 different bioprocesses.

Microbiological analysis, qualitative and quantitative chemical analysis (IR, GC-MS) have been performed to follow the evolution of the oil ; results are discussed here below.

1. INTRODUCTION

Among the many techniques proposed for restoring a polluted coastline, the processes involving oil biodegradation are currently being studied and improved.

The use of these techniques has evolved as a result of the Exxon Valdez accident in Alaska when "fertilizer type" products for biodegradation were massively employed.

* CEDRE : Center for Documentation, Research and Experimentation on Accidental Water Pollution

** SHOM : French Navy's Hydrographic Office

*** MNHN : National Museum of Natural History of Paris

In order to clarify some questions concerning bioremediation agents, CEDRE was allowed to realize long term experiments on a beach belonging to the French Navy.

Conducted over a one year period in close collaboration with EPSHOM and MNHN, these tests aimed at assessing the fate of an oil treated by various biodegradation agents and processes over a period of one year.

2. EXPERIMENTAL OBJECTIVES

In addition to observing the biodegradation of a crude oil and to obtaining a generalized "first evaluation" concerning the various bioremediation agents tested, the experiments were also intended to define and improve an experimental testing method which would enable subsequent evaluations concerning the effects of various biodegradation processes and products.

3. TESTING

3.1. Testing Site

The test area is a beach located in the Brest Bay on the western coast of France (Brittany).

The beach is a pebbles spit sheltered behind a little rocky island, and is composed of a mixture of large grained sand (sea-shells debris) and shingles.

The slope of the beach is on the order of 10 %.

3.2. Experimental Set-up (fig. 1)

Six 3 m² test plots were prepared in the intertidal zone at a height of 3.5 m above 0 (according to maritime charts, lowest sea level). Each test plot was enclosed by a breeze-block wall designed to protect the plot from extensive wave action. Two crates containing sand from the nearby beach area were placed within the breeze-block enclosures of each test plot.

The experimental plots were built about 1 month before the oil was applied.

3.3. Type of Pollutant

The testing was done using a light Arabian crude (BAL) topped at a temperature of 110°C.

3.4. Application of the Pollutant

The oil was applied (on the whole surface of each test plot) for a total concentration of 5 liters/m², in two consecutive applications of 4 liters and 1 liter which were respectively accomplished 14 days and 10 days before the bioremediation agents were applied.

3.5. Biodegradation Processes to be tested

Four different processes were evaluated.

3.5.1. **Process Nr. 1** involved the application of amicroflora adapted to the specific task of oildegradation. The freeze-dried bacteria enriched with additional nutritive elements were prepared several hours before application premixed with water with a specific additional ingredient (Tested in Test plot No. 1).

3.5.2. **Process Nr. 2** involved the use of an adapteddehydrated bacteria packed in small 50 gram net bags. The small bags were re-hydrated in sea water 20 minutes before being applied (Test plot No. 2).

3.5.3. **Process Nr. 3** involved an already known bioremediation formula of nutritive nitrogen and phosphorous which was previously used during the Exxon Valdez clean-up inAlaska (Reference : 1).

This product, defined as a "biodegradation starter" is designed to acts as a stimulus for indiginous bacteria (Test plots Numbers 3 and 5).

3.5.4. **Process Nr. 4** used a fine-grained, non water repellant chalk powder which is intended to favorize the action of indigenous bacteria by increasing the surface area for effective bacteria fixation (Test plot No. 6).

Test plot Nr. 4 was left un-treated in order to serve as a control plot.

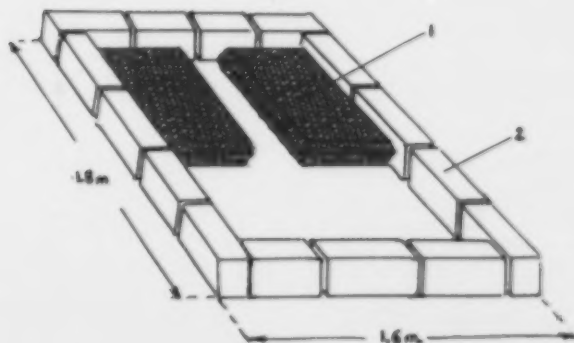


FIG. 1 - Experimental set up
1. Protection made with breeze-blocks
2. Crates containing sediment

4. ANALYTICAL METHODS

In addition to visual observations and photographs at the site, the methods employed in the evaluation included sampling and laboratory analyses :

- micro-biological analyses : comparison between the total microscopic bacteria and the microscopic bacteria specifically adapted to oil degradation (reference : 2 and 3).
- measurements of oil concentration in the sediment using spectrometry and infra-red analyses (reference : 4).
- qualitative analyses of the oil after its separation into various families (Cf. Annex 1) using gas chromatography methods on aliphatic and sulfur containing aromatic fractions (analyses made by EPSHOM) (reference : 5 and 6).
- qualitative analyses of the oil by gas chromatography coupled with mass spectrometer (analyses made by MNHN)
- measurements of the nitrogen (Kjeldhal) and phosphorous-concentrations in ambient sea-water.

The samples were taken from the test plots, and from surrounding beach areas to serve as control samples (non polluted area), at several meters from the test plots as well as at several tens of meters from the test plots.

Each time an "average sample" was prepared for a given test plot ; it was made by mixing ten random samples from the plot.

5. CHRONOLOGY

(Cf. Annex 2)

6. FIRST TEST RESULTS

At the present time, we have analyses available from samples taken during the first 4,5 months of the evaluation period.

6.1. Micro-biological analyses

Annex 3 presents the evolution of bacterial population (bacteria adapted to hydrocarbon and total bacteria) during the first 4.5 months of the evaluation period.

6.2. Oil concentration in sediment

Annexes 4 and 5 present the evolution of the oil concentration in the sediment measured by colorimetric spectrometry and by infra-red spectrometry.

6.3. Qualitative oil analyses using chromatography

Annexes 6 and 7 present several examples of chromatographic analyses on samples taken after two months for the aliphatic and aromatic oil fractions. Analyses have been done for test plot 4 (control plot) and for the more degraded oil in plots 2 and 3 (processes 2 and 3). Similar chromatographic analyses were made after 4.5 month, however they do not reveal a more advanced stage of oil degradation.

NOTA : only the mass spectrography analyses of the two first months have been yet performed on plots 2 and 4 and they confirm GC analyses).

6.4. Nitrogen and phosphorous concentrations

The nitrogen content of the surrounding sea water was determined to be 0.34 mg/l at the beginning of the test period and 0.15 mg/l after 2 months (total Kjeldahl nitrogen).

As far as the phosphorous content is concerned, a quantity of 0.09 mg/l (total phosphorous) was determined at the beginning of the test period as well as two months later.

7. DISCUSSION

7.1. Studies of the biodegradation processes

The microbiological data mainly show that specifically adapted bacteria are much developed in the polluted plot than in the surrounding area (non polluted control).

The oil concentration in the sediment has rapidly decreased (about 80 - 90 % according to the I.R. measurements), and this can be explained by the tides action and wave washing effects.

The plots located at the two ends of the set-up are more exposed to the sea's washing action, especially plots 1, 5, and 6. The waves' action was so intense that they were able to loosen and displace some of the breeze blocks. The oil concentrations decreased immediately at the beginning of the experimental period (between 8,000 - 11,000 ppm according to the I.R. measurements) and this concentration decreased increasingly more quickly in the more exposed test plots. For the plots 2 and 3 which were less exposed to the waves' action, the oil concentrations at the beginning of the test period were greater (between 13,000 - 18,000 ppm according to the I.R. measurements), and the decrease in oil concentration required a longer period of time.

After 4.5 months, the difference in the oil concentration for the five treated test plots is less apparent (between 4,400 and 2,000 ppm according to the colorimetric analyses); at this point, only the oil strongly adsorbed on the sediment still remains.

Whether they were made on samples recovered after 2 or after 4.5 months, the chromatographic analyses have revealed only a small amount of biodegradation.

Nevertheless, test plots 2, 3 and 5 have shown a significant degradation when compared to the control plot (despite the fact that their oil content is somewhat higher than in the other test plots).

The table 1 presents the percentage of oil which has been biodegraded (for the medium weight alkanes) in comparison with the original crude of oil and with the oil of the un-treated control plot (calculated according to the method of Bodennec & al. reference 7) :

$$(nC17/Pr)_o - (nC17/Pr)/(nC17/Pr)_o$$

where :

(nC17/Pr) is the ratio nC17/Pristane of the test plot.

(nC17/Pr)_o is the ratio nC17/Pristane of the reference (oil initially applied, B.A.L. or the control plot, untreated).

	Reference	nC17/Pr	nC18/Ph	Pr/Ph	% biodegradation	
					B.A.L.	Plot 4
	B.A.L.	6.67	3.13	0.56	-	
Process 1	Plot 1	4.17	2.22	0.56	34.9	0
Process 2	Plot 2	2.63	1.37	0.54	59.1	36.8
Process 3	Plot 3	2.78	1.47	0.56	57.4	33.3
Control	Plot 4	4.17	2.33	0.55	35.4	-
Process 3	Plot 5	3.57	2.04	0.55	45.1	14.3
Process 4	Plot 6	4.17	2.38	0.56	34.9	0

Table 1 : Evaluation of the percentage of Biodegradation

The chromatographic analyses of the sulfur containing aromatic fractions confirm the prior results. For all the test plots, we observe an almost total disappearance of the benzothiophenes (which might also be partially due to the phenomenon of evaporation); however, the disappearance of the dibenzothiophenes and their methyl derivatives for test plots 2 is attributed to the result of biodegradation.

These findings have led us to the conclusion that processes 2 and 3 (tested in plots 2, 3, and 5) have had a favorable effect on the oil biodegradation. Nevertheless, when taking into account the original composition of the oil, and according to previous work which has been done to assess the relative length of time necessary for the biodegradation of various oil fractions (reference 8), we can estimate that the total of degradation (when compared to the whole composition of the oil), is on the order of only 10 - 15% of the total original oil for test plots 1, 4, 6 and about 20 % for the test plots 2 and 3. This corresponds to the first stage of biodegradation as defined by Oudot-Dutrieux (reference 9).

It is interesting to note that after 4.5 months in situ, the biodegradation which has occurred is on the same order as what was obtained after only a few days under optimal laboratory conditions (nutritive minerals, temperature, bacteria, etc.), (reference 8). Available nitrogen is apparently a limiting factor : a quick calculation using as reference an optimum ratio C/N = 10), shows that the nitrogen concentrations in sea water (0.15-0.3 mg/l) enable, in the best case situation, (where the total amount of available nitrogen is consumed), a biodegradation of 10 to 20 ppm of oil in the sediment per month, (which is much less than the oil concentrations actually observed in the test plots).

7.2. Experimental Methods

Although the beach area selected for the test site was relatively protected, there was still a fairly strong agitation (waves, etc.) which caused much sediment movement along the shore.

Under such conditions, the use of crates to hold the polluted sediment was seen to be a good solution for such long term testing.

For any further test, the method can be improved especially by half buried the crate of sediment in the beach rather than simply set them on the beach surface ; in this manner, the polluted sediment will be under more realistic conditions in terms of the agitation, wave action, percolation, etc.

The variations in the oil concentrations in the sediment from one sampling site to another (due to the amount of pollution and the sediment granulometry) give proof of the sediment heterogeneity within each crate.

In terms of comparing the various bioremediation agents, it will be better to use a sifted sand (to provide a more uniform sand grain size), and to thoroughly mix the oil with the sediment (in a mixing machine).

Observations have shown that the test site, although relatively small (~ 60 m), does not present the same oceanic conditions ; it was especially noticeable that the beach's extremities were more exposed to the waves' agitation than the center.

In order to overcome these local variations, it will be preferable to test each individual product in at least two (and better yet, three) test plots located at various sites along the beach.

8. CONCLUSIONS

Under the given oceanic-temperate test conditions, this long term study has clearly shown that the oil biodegradation in surface sediment along the coast takes place very slowly and that the oil's disappearance is principally due to wave washing action and the effects of the tides.

Then these tests, which were initially planned to cover a period of six months, will be extended for a total of one year.

The main factor limiting the biodegradation of oil is the availability of nitrogen; this emphasizes the need for the development of bioremediation products able to progressively provide the correct amount of necessary nutrients.

The tested products were not proven to be of any particular effectiveness. Only the Processes 2 and 3 were able to show a slight increase in the oil's biodegradation and this observation should be confirmed in the test follow-up.

The experimental methods (especially the use of crates for holding polluted beach sand) will enable us to perform a long term study of the oil's evolution in the absence of perturbing external elements such as waves, storms, sediment movement, etc.

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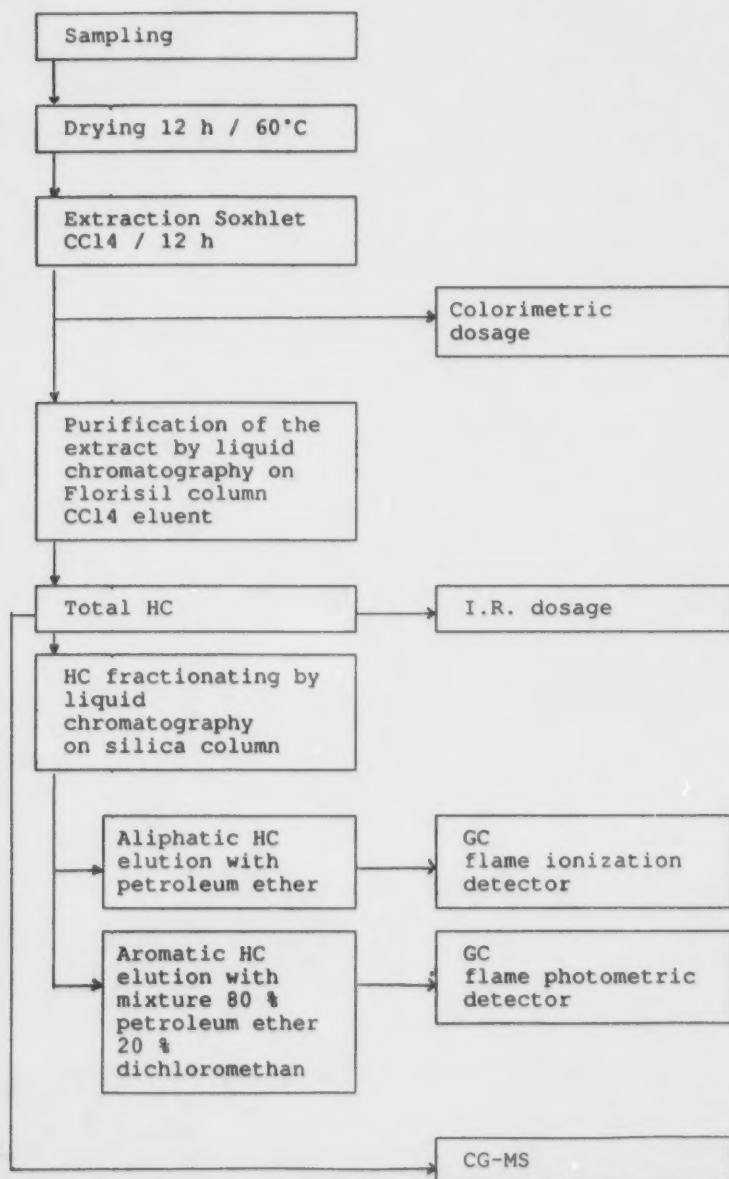
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ANNEX 1

PURIFICATION, FRACTIONATION AND ANALYSES
OF OILY SEDIMENTS SAMPLES

ANNEX 2

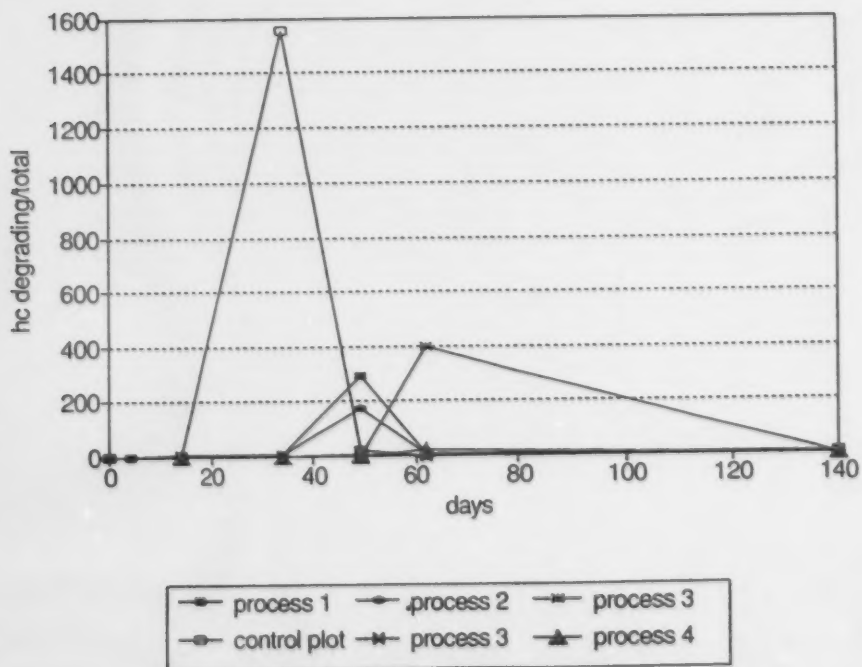
CHRONOLOGY

	ANALYSES							
Time (days)	Bacterio	Quantitative			Quali- tative			
		Colorimetry	I.R.	Gravimetry	GC	GC-MS		
- 42	Preparation of test plots on the beach							
- 14	X							
	First application of oil on test plots							
- 10	Second application of oil on test plots							
- 3		X	X				X	
0	X							
	First application of biodegraders (plots : 1, 2, 3, 5, 6)							
4		X	X					
14	X							
	Second application of biodegraders (plots : 1, 2, 5, 6)							
34	X	x	x					
	Third application of biodegraders (plots : 1, 2, 5)							
49	X							
62	X	X	X	X	x	x (plots 2, 4)	X	
140	X	X	X	X	X	X		
futur (#240)	X	X	X	X	X	X	X	
(#365)	X	X	X	X	X	X		

ANNEX 3

RATIO HC degrading microbial population/total population

process days	n 1	n 2	n 3	control	n 3	n 4	control unpollute area 1	control unpollute area 2
0	0,13			0,56			0,41	0,00
4	3,11	0,04					0,02	
14	4,74	0,00	0,00	0,10	0,01	0,00	0,04	0,00
34	6,00	6,25	0,16	1555,56	0,09	0,40	0,04	0,00
49	291,67	175,00	0,00	22,73	9,33	1,56		
62	4,74	4,74	400,00	0,00	1,80	23,75	1,80	0,03
140	0,42	4,74	1,00	9,47	0,06	0,08	0,20	0,02

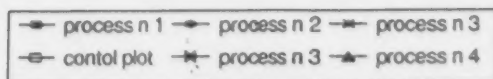
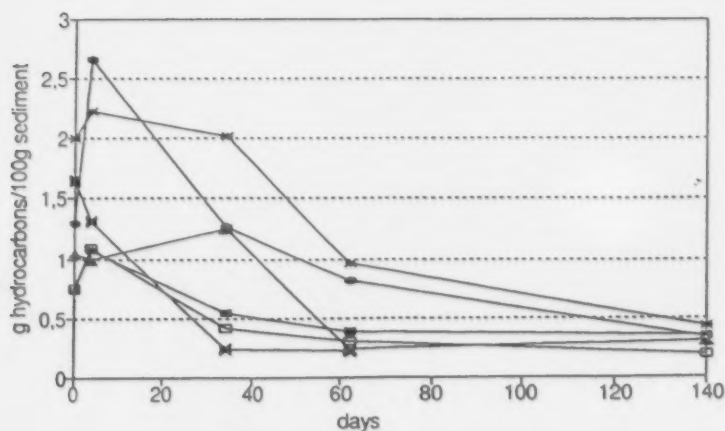


ANNEX 4

HYDROCARBON CONCENTRATIONS VERSUS TIME

(Spectrocolorimetry method)

process days	n1	n2	n3	control	n3	n4	control unpolluted area 1	control unpolluted area 2
0	0,74	1,30	2,00	0,76		1,05		
4	1,07	2,66	2,22	1,08	1,65	0,99	0,030	
34	0,54	1,26	2,02	0,42	1,31	1,25	0,020	0,020
62	0,38	0,81	0,96	0,30	0,24	0,25	0,009	0,002
140	0,35	0,34	0,44	0,2	0,22	0,3	0,007	0,018

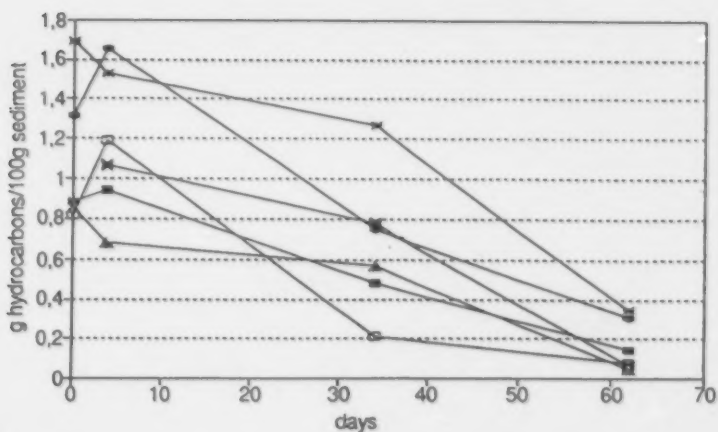


ANNEX 5

HYDROCARBON CONCENTRATIONS VERSUS TIME

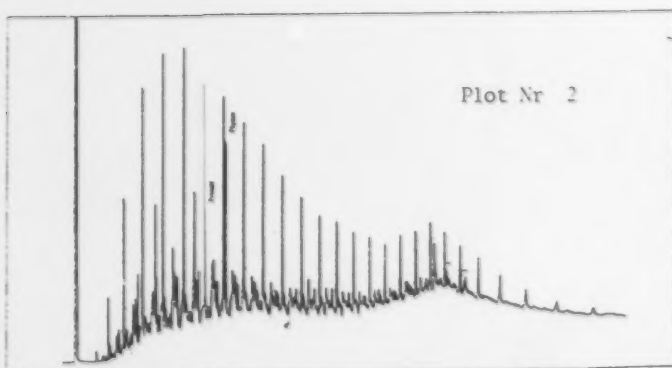
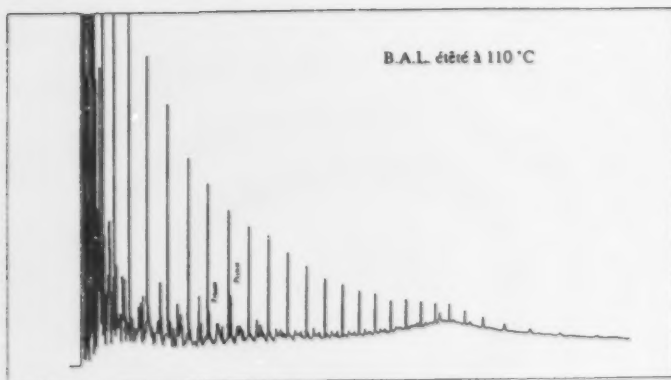
(Infrared measurement method)

process days	n.1	n.2	n.3	control	n.3	n.4	control unpolluted area 1	control unpolluted area 2
0	0,88	1,32	1,69	0,82		0,86		
4	0,94	1,65	1,53	1,19	1,07	0,68	0,005	
34	0,48	0,75	1,27	0,21	0,78	0,57	0,02	0,002
62	0,14	0,31	0,35	0,08	0,07	0,05	0,002	0,02

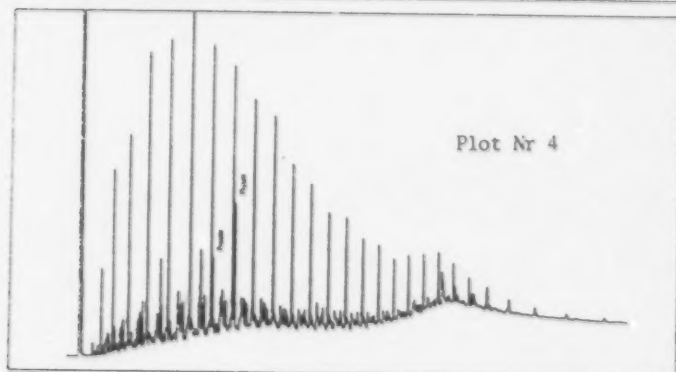
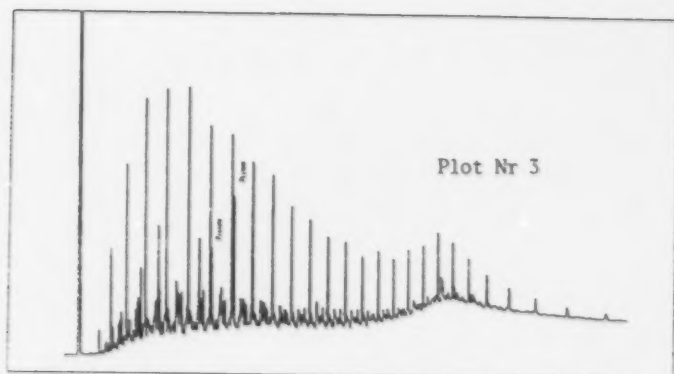


—■— process n 1 —◆— process n 2 —▲— process n 3
 —○— control plot —×— process n 3 —*— process n 4

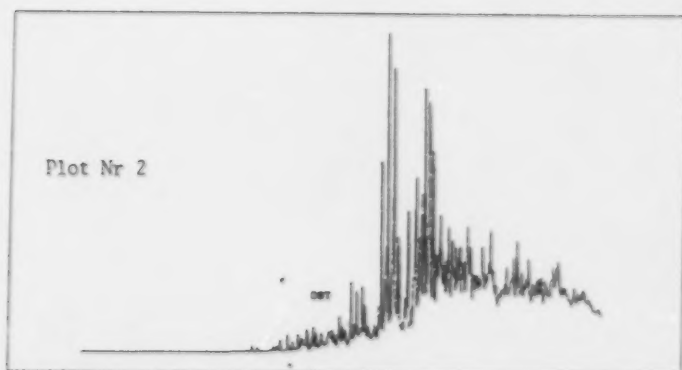
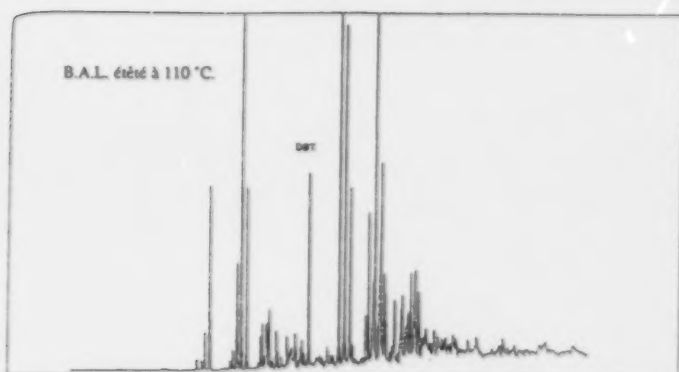
ANNEX 6
GC of aliphatic fractions



(continued)



ANNEX 7
GC of sulfur containing aromatic fractions



BIOREMEDIATION EFFICACY IN MARROW MARSH FOLLOWING THE APEX OIL SPILL, GALVESTON BAY, TEXAS

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The U.S. Environmental Protection Agency's Environmental Response Team analyzed samples taken from Marrow Marsh, Galveston Bay, Texas, to assess the efficacy of the August 5, 1990 bioremediation treatment in the marsh following the Apex barge oil spill on July 28, 1990. The bioremediation treatment combined a hydrophilic bacterial mixture and a nutrient mix containing phosphorus and nitrogen. Samples from the marsh had been collected over a 96-hour period from both treated and untreated oiled sites. Oil fingerprinting, fatty acid analysis, polynuclear aromatic hydrocarbons analysis and total petroleum hydrocarbons analysis were performed to evaluate changes in the chemical characteristics of spilled oil. Results of analyses, although not statistically reliable, failed to support the occurrence of any definite chemical alteration in the spilled oil that could be attributed to the bioremediation treatment. The relatively short sampling period and the number of samples taken, however, may have been insufficient to document the efficacy of the overall bioremediation effort.

INTRODUCTION

Evaluating the efficacy of the use of bioremediation agents in any spill situation requires consideration of at least two important issues: (1) whether biodegradation of the spilled oil is occurring and (2) whether the agents added to the spilled oil are actually having a net positive effect on the oil-biodegradation process. In Alaska, the efficacy of bioremediation was demonstrated by measuring the number of hydrocarbon-degrading microorganisms, microbial hydrocarbon-degrading activities and chemical changes in residual oil.^{1,2} This article addresses an approach that was used by the U.S. Environmental Protection Agency's (EPA's) Environmental Response Team (ERT) to evaluate changes in chemical characteristics of oil spilled from the Apex 3417 and Apex 3503 barges in Galveston Bay, Texas, in the summer of 1990. In particular, it addresses the chemistry of the alteration of spilled oil in Marrow Marsh following the application of commercially available bioadditives.

Incident Description³

On July 28, 1990, the Greek tankship *Shinouma* collided with and sank the tank barge Apex 3417 and damaged the barge Apex 3503 in the Houston Ship Channel, Galveston Bay, Texas. The damage to the two barges resulted in the discharge of about 692,000 gallons of catalytic feedstock oil into the waters of Galveston Bay over a 2-day period. The owner and operator of the barges, Apex Towing Company, Inc., quickly accepted responsibility for the spill and, under the direction of the U.S. Coast Guard, began deploying boom to contain the oil at the barges. The Texas Water Commission and EPA Region 6 were notified not long after the incident and began to activate response personnel.

Under the influence of changing winds and tidal currents, the oil migrated throughout the Bay, threatening shorelines and environmentally sensitive marshes; deployment of booms, beach cleanup and efforts to recover floating oil were intensified. Early in the response, as the size and seriousness of the spill became more apparent, the Chairman of the Texas Water Commission and the Deputy Commissioner of the Texas General Land Office both contacted the On-Scene Coordinator (OSC) urging that bioremediation be considered to mitigate the spill. The OSC indicated that any treatment (1) would have to be paid for by the state or the

responsible party, (2) could not interfere with other cleanup activities and (3) would have to be reviewed by the Region 6 Regional Response Team (RRT) and approved in accordance with Subpart H of the Regional Contingency Plan (RCP). On the request of the OSC, the use of the Alpha BioSea process (developed by Alpha Environmental, Austin, Texas) was approved -- contingent on a number of guidelines -- for areas where mechanical cleaning would do more harm than good. (The Alpha BioSea process combines a lyophilized bacterial mixture in a corn starch carrier and a blue-colored nutrient mix containing inorganic water-soluble phosphorus and nitrogen.)^{4,5}

Applications of the bioremediation agent were made according to instructions of the product vendor in marsh areas of Pelican Island and in selected areas of Marrow Marsh, a salt marsh that is dominated by 1 to 1.5 m tall marsh grass and generally protected from heavy wind and wave action.⁶ Beginning just prior to the initial application in Marrow Marsh eight days after the spill incident occurred, monitoring teams from the Texas Water Commission -- with assistance from Texas Parks and Wildlife, EPA, and National Oceanic and Atmospheric Administration (NOAA) -- took periodic samples from designated treatment and control sites for analysis to assess the effects of the treatment.

EPA's Involvement in Response Activities

EPA Region 6 provided technical expertise during the *Aper* spill response. Also, in accordance with the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) and the Region 6 RCP, regional EPA representatives played a major role in deciding whether the application of bioremediation agents in Galveston Bay would be approved. In addition, several regional EPA representatives served on an ad hoc committee to identify the need and acceptable procedures for applying bioremediation agents to oiled areas in Galveston Bay as a result of the *Aper* spill.

ERT became involved in response operations following the *Aper* spill, and particularly the ensuing bioremediation activity, on the request of EPA Region 6. Initially, ERT provided expertise from previous bioremediation projects conducted in Alaska and Fralls Island (located on the Arthur Kill between New York and New Jersey), although ERT took no part in designing or implementing the monitoring program used in Marrow Marsh. Later, on the request of EPA Region 6, ERT performed analyses of samples taken from designated treated and untreated sites in Marrow Marsh to determine the effects of the bioremediation treatment.

SAMPLING AND ANALYTICAL METHODOLOGIES

The bioremediation agent application plan and the monitoring program used in Marrow Marsh were developed by the Texas Water Commission in coordination with its contractors. Methods for analyzing samples were selected and performed by ERT and its contractors.

Sampling Scheme

Four test sites or plots were established:^{7,8} two treated (A1 and A2) and two control or untreated (A3 and A4). Plots were about 50 feet in diameter or less and separated by 150 to 250 feet. Surface material and non-moveable material within a test site were isolated with containment boom. An absorbent boom and a non-absorbent boom were also deployed around the entire marsh test-area.

The sampling scheme called for three replicate grab samples to be taken at each of the four test sites at three water depths: (1) surface, (2) mid-water (about 10 to 30 centimeters below surface), and (3) bottom, to include the top 2 centimeters of mud.⁹ (In most areas of the marsh, the water depth is no more than about one foot.)¹⁰ Sampling was nominally performed 30 minutes prior to and one hour, 24 hours, 48 hours and 96 hours after microbial treatment on August 5, 1990. Because some samples were missed (no control

samples were collected one hour after treatment and two 24-hour samples from treated sites were missed), a total of 160 samples, rather than the 180 intended, were collected.

Samples were collected in 32 ounce mason jars that had been cleaned with methylene chloride prior to use. All samples were labelled with a sample identification number and a sample location code. The location code reflects the (1) sampling site (i.e., A1, A2, A3 or A4), (2) sampling trial or "grab" number (i.e., G1, G2 or G3), (3) depth of sampling (i.e., "SURF", "MIDW" or "MUD"), and (4) sampling time (see Table 1). Samples were frozen soon after collection and later stored at the Texas Water Commission in Houston, Texas.

PARTIAL SAMPLE LOCATION CODE	TIME OF SAMPLING RELATIVE TO TIME OF MICROBIAL AGENT APPLICATION
PRE	Pretreatment (before application)
POST	1 hour after application
P24	24 hours after application
P48	48 hours after application
P96	96 hours after application

TABLE 1. Time labelling scheme for water samples from Marrow Marsh.

On September 19, 1990, ERT received for analysis 117 of the 160 samples collected from Marrow Marsh during the approximately 4-day sampling period following the August 5, treatment; the Texas Water Commission had retained one of the three replicate grab samples taken from each sampling site and water depth whenever sampling was performed, and a few samples were accidentally destroyed. On October 22, 1991, ERT received for analysis the remaining grab samples collected from Marrow Marsh. However, because the results of analyses of these samples have not as yet been thoroughly evaluated, they are not included here.

Description of Methods

Sample analyses were designed and performed with two primary objectives: (1) to determine the relative concentration or presence of the major constituents in the spilled oil (and changes in their concentration or presence with time) that would indicate the fate of the oil in the environment and (2) to characterize changes in constituents of spilled oil that would be consistent with or could be attributed to biodegradation.

In designing the chemical characterization experiments to achieve these objectives, analytical methods that are selective and sensitive for constituents and degradation products of oil were chosen. Oil fingerprinting using GC and GC/MS with selected ion monitoring were performed because they have been used historically to determine hydrocarbon constituents of oil in water and sediment samples. The target hydrocarbons and hydrocarbon ratios C17/pristane and C18/phytane were evaluated specifically because they have been used and are a recommended means to assess changes in hydrocarbon constituents that may be attributed to microbial degradation.¹¹ A method for analyzing fatty acids by GC was selected because fatty acids are intermediate products of microbial degradation of *n*-alkanes that have been found to accumulate during hydrocarbon degradation.¹² In addition, the developer of the microbial system used in Marrow Marsh suggested that fatty acids could be observed as evidence of biodegradation. The C3 to C10 analysis range for fatty acids was selected because it was assumed that this range would be the repository for intermediate molecular weight alkanes undergoing degradation. Methods of analyzing polynuclear aromatic hydrocarbons by GC/MS with selected ion monitoring and total petroleum hydrocarbons by IR were selected to assess broad changes in the amount and constituents of oil over time.

Ensuring statistical validity of results of analyses was constrained by two conditions: (1) the limited number of samples available for analysis (i.e., two replicates per sampling site, water depth and time) and (2) the sample size requirements of each analytical method. In most cases, these conditions restricted the availability of samples for any particular analytical method to a maximum of one sample replicate per site, water depth and time (or a maximum of about 54 samples).¹

Oil Fingerprinting by GC with Flame Ionization Detection

Oil fingerprinting by GC with flame ionization detection was performed to quantify the C17/pristane and C18/phytane ratios by peak area. Oil-fingerprint analysis was performed using ASTM Method D3328.

Sample preparation

Surface and mid-water samples were prepared according to Contract Laboratory Practice (CLP) protocol for Base-Neutral/Acid (BNA) analysis using a sample volume of 500 ml. BNA surrogates were added to each sample prior to preparation, although quantitation was not required.² The acid and base fractions were extracted and analyzed separately. Bottom-water (or mud) samples were prepared by extracting 30 grams of each sample three times with 100 ml of dichloromethane, pouring-off and collecting the dichloromethane portion between additions of solvent. The collected liquid was then concentrated to 1.0 ml. Barge and reference oil samples simply were diluted with dichloromethane before GC and GC/MS analyses.

Generally, as part of the QA/QC procedures employed, matrix spike and matrix spike duplicate (MS/MSD) extractions would have been performed to evaluate and confirm extraction efficiency. Because the volume of the water samples was not sufficient to perform MS/MSD extractions (the procedure requires 1 liter of water per sample), however, spiked blanks were analyzed using deionized water (five pairs were analyzed). Because there was an abundance of mud from bottom-water samples, one mud sample was spiked for MS/MSD analysis. All blank and MS/MSD samples were spiked prior to extraction with a C17 and C18 mixture to yield a final concentration of 50 ug/ml of each compound in the final 1.0 ml extract volume. One water blank was also spiked with the BNA MS/MSD compounds to further check extraction efficiency for BNA compounds.

Instrument preparation and calibration, and analysis

Sample analysis was performed using an HP Model 5890A GC, equipped with a flame ionization detector and attached to an HP auto sampler and integrator. The instrument conditions were as follows: column: Restek Rtx-1, 30 meter x 0.53 mm ID, 0.5 um film; temperature program: 40°C for minute, 8°C/min to 310°C and held for 10 minutes; injection volume: 2.0 ul; detector operation: 275°C; injector temperature: 250°C; and flow: helium at 8 ml/minute.

A 5-point calibration range for C17 and C18 was prepared and analyzed. To prepare the calibration standards, a standard mixture of C17 and C18 was prepared from Aldrich standards and then diluted to 5.0 ng/ul through 200 ng/ul of each C17 and C18 using dichloromethane. On start-up each day, a standard of C17 and C18 was injected and checked against the calibration range for any variability (± 25 percent was acceptable).

Two other mixtures, a qualitative resolution mixture of eleven straight-chain paraffinic hydrocarbons ranging from C10 to C36, and a confirmation mixture of known amounts of C16, C18, and C20 standards, also were prepared; these mixtures were analyzed daily once

¹ The value 54 takes into account that samples were not collected from untreated sites one hour after application of the bioremediation agent.

² BNA surrogates were used qualitatively to monitor the extraction efficiencies from the lab.

calibration checks passed.³ The qualitative resolution mixture (called a "P-11 mix") was analyzed to provide retention time indices and a measure of compound resolution as dictated by Method D3328. The quantitative mixture was analyzed to confirm the identity of peaks corresponding to C16, C18 and C20 in the chromatograms for the P-11 mix.

Prior to analysis, each sample extract was spiked with 10 μ l of 5,000 μ g/ml 2-chlorooctane as a qualitative internal standard to monitor the splitless efficiency. No calculations were performed with this internal standard; however, if less than a 50 percent level of the internal standard was detected visually, the sample was rejected. Analyses were performed on the base fractions of the sample extracts only (except those of combined extracts). Hydrocarbon ratios were computed by directly comparing the relevant integrated peak areas.

On February 2, 1991, a sample of barge oil – representative of the oil spilled in Galveston Bay from the *Aper* barges – was obtained and analyzed for fingerprinting. The resultant fingerprint was then compared to those for several standard reference oils. The reference oils used for comparison were (1) No. 2 fuel oil, (2) Frudhoe Bay oil, (3) South Louisiana crude oil, (4) Bunker C oil and (5) Arabian crude oil. This exercise was conducted to verify the identity of the barge oil, although it was not necessary to perform the analyses.

Oil Fingerprinting by GC/MS

Oil fingerprinting by GC/MS using the BNA method was performed for 13 water sample extracts (i.e., fractions from the BNA extraction procedure above), one surface oil sample and one barge oil sample. Each sample extract selected for GC/MS analysis generally met the two following criteria: (1) atypical or unknown peaks appeared in the fingerprint (or chromatogram) for the sample and (2) sample was representative of atypical or unknown peaks recurring in all sample fingerprints, or in fingerprints for all samples in a sampling category (e.g., untreated surface-water samples) and time period (e.g., 24 hours after applications).

Sample preparation

The surface oil sample and the barge oil sample were simply diluted and injected in order to minimize any weathering or pattern changes associated with the extraction process. The 13 fractions from environmental samples, as well as two water blanks, were analyzed without further preparation.

Instrument preparation and calibration, and analysis

Sample analysis was performed on an HP Model 5995C GC/MS, equipped with a 7673A autosampler and controlled by an HP-1000 RTE-6/VM computer. The instrument conditions were as follows: column: Restek Rtx-5 (cross-bonded SE-54), 30 meter $\times$ 0.32 mm ID, 0.5 μ m film; temperature program: 30°C for 3 minutes, 15°C/min to 70°C and held for 2 minutes, then 8°C/min to 295°C and held for 12 minutes; injection Volume: 2.0 μ l; splitless injection: split time of 60 seconds; injector temperature: 250°C; transfer temperature: 290°C; source temperature: 220°C; analyzer temperature: 220°C; and flow: helium at 8 ml/min.

The GC/MS system was calibrated using five BNA standards at 20, 50, 80, 120, and 160 μ g/ml. The calibration range was validated by evaluating the System Performance Check Compounds (SPCC) and Calibration Check Compounds (CCC) as outlined in the CLP protocol. Each day before any analyses were performed, the system was tuned to DFTPP and passed a continuing calibration check when analyzing a 50 μ g/ml standard mixture in which the

³ Because the identity of peaks corresponding to C19, C20, C30, pristane and phytane is generally obvious in the "fingerprints" for most oils, it was not necessary to analyze standards for these oil constituents.

responses of the SPCC and CCC compounds were evaluated by comparison to the average response of the calibration curve.

Prior to analysis, all sample extracts were spiked with the GC/MS internal standard specified in CLP protocol. Samples were analyzed using normal BNA calibration and conditions. Extracted ion profiles were plotted for all samples that had a GC chromatogram resembling the reference oil fingerprint. Ion 43 was selected because it is the most abundant ion when fragmenting hydrocarbons.

Fatty-Acid Analysis by GC with Flame Ionization Detection

Fatty acid analysis of *Apex* oil spill samples from Marrow Marsh was performed by the University of Rhode Island using capillary GC, with a minimum detection limit for fatty acids of 3 ppm. The method used to analyze free fatty acids (C3 to C10) in oil, water, and mud fractions of 53 samples was developed by the subcontract laboratory.

Sample preparation

All samples were kept frozen at about -20°C prior to sample preparation and analysis. Once samples were thawed for preparation, they were kept on ice to prevent evaporation of any existing volatile fatty acids. All samples (i.e., matrix spikes) were prepared and analyzed in duplicate.

Each sample, where appropriate, was separated into water, mud, and oil fractions. Water fractions were centrifuged when necessary to remove debris and then analyzed directly by GC. Aliquots of oil and, separately, of mud were weighed on an analytical balance and the weights recorded. Weighed mud and oil samples (0.2000 grams and/or 1.0000 gram duplicates) were then placed in individual teflon-lined screw-cap glass centrifuge containers, spiked with standard fatty acids and saponified using 10 ml of 0.5 N KOH in methanol. The samples were capped and heated under nitrogen in a 100°C water bath for 20 minutes. After heating, aliphatic hydrocarbons were removed from each sample by washing twice with 10-ml aliquots of petroleum ether (PE). The PE layer of each sample was removed and discarded after each wash; the salts of any fatty acids remained in the methanol/alkali fractions. These fractions were washed with 5.0 ml of water each, which caused the residual PE to separate for removal. After removing residual PE, the mixtures were transferred to individual 125-ml separatory funnels. Each methanol/alkali mixture was acidified with 20 ml of 2 N HCl to yield free fatty acids (if present) and to adjust the polarity of the solution.⁴ Any free fatty acids that were present in each mixture were then extracted twice with 20-ml aliquots of chloroform. For each sample, the chloroform washes (about 40 ml total) were collected in a 50-ml volumetric flask that was subsequently brought to volume.

Instrument preparation and calibration, and analysis

Fatty-acid analysis were performed on a Carlo Erba Fractovap Model 4160 GC, equipped with a flame ionization detector and attached to a Hitachi Model D-2500 recording integrator. The instrument conditions were as follows: column: Supelco Nukol capillary GC column (polyethylene glycol bonded to fused silica); temperature program: isothermal at 175°C; injection volume: 2.0 µl (50:1 split injection); detector operation: 200°C using 24 ml/min hydrogen and 240 ml/min air; injector temperature: 210°C; and flow: Helium at 20 ml/min.

Prior to analyzing samples, quantitated fatty-acid standards were injected each day to ensure instrument calibration.⁵ Standards for evaluating analyses of both oil and mud fractions were prepared in chloroform; standards for evaluating water were prepared in

⁴ Adjusting the polarity of the solution was intended to ensure maximum migration of shorter-chain fatty acids into the organic phase during later washes with chloroform.

⁵ Individual free fatty-acid standards were obtained from Sigma Chemical, St. Louis, Missouri.

methanol.⁶ In addition, the fatty-acid content in butter samples was analyzed daily and compared with published data as presented in the USDA Agriculture Handbook No. 8-1. The linear range evaluated in this study was from 10 ppm to 500 ppm for all fatty acids.

Fatty acids were identified and quantified by comparing relative retention times and areas of sample peaks with those obtained for C3 through C10 fatty-acid standards. Recovery was calculated as a percentage of the quantity of the standard fatty acids added.

Polynuclear Aromatic Hydrocarbons Analysis by GC/MS with Selected Ion Monitoring

Four pretreatment and four 96-hour bottom-water (mud) samples, one from each sampling site, and one barge oil sample were analyzed for polynuclear aromatic hydrocarbons (PAHs) using GC/MS with selected ion monitoring. Mud samples were prepared by sonicating 30 grams of each sample three times with 100 ml of methylene chloride. Prior to extraction, each sample was spiked with 500 μ l of 10 μ g/ml of BNA surrogate compounds. Sample extracts were then concentrated to 1 ml using a KD apparatus and subsequently eluted through a silica gel clean-up column (100/200 mesh) with 15 ml of hexane and 45 ml of a hexane:benzene (1:1) mixture. The eluate of each sample was concentrated to a final volume of 1 ml. The oil sample was simply diluted 50 times in methylene chloride; no BNA surrogate compounds were added.

Sample analysis was performed on an HP Model 5995C GC/MS. The conditions and column used were the same as those described above for oil fingerprinting by GC/MS; however, the selected ion monitoring mode was employed rather than the linear scanning mode. The scanning ions were broken down into 12 groups for maximum sensitivity. The instrument was tuned for DFTPP and a six-point calibration range from 0.1 to 10 μ g/ml of the 16 PAH standards that were used.

Total Petroleum Hydrocarbons Analysis by Infrared Spectroscopy

Fifty-two water samples (comprised of 16 surface-water samples, 18 mid-water samples, and 18 bottom-water (mud) samples) were analyzed for petroleum hydrocarbons by infrared spectroscopy. All samples were prepared and analyzed following CLP Protocol.

RESULTS

Oil Fingerprinting by GC with Flame Ionization Detection

Tables 2, 3 and 4 list the C17/pristane and C18/phytane ratios for surface-water, mid-water, and bottom-water (mud) samples, respectively, that were collected from both treated and untreated sites. For a basis of comparison, each table also lists these ratios for the analysis of barge oil (catalytic feedstock oil). Generally, decreases in the ratios over time may be interpreted as an indicator of biodegradation. All ratios were calculated using the area counts provided by the integrator for relevant chromatogram peaks.

⁶ The choice of methanol and chloroform to dissolve standards is consistent with sample preparation procedures for water, mud, and oil samples.

SAMPLE ID	LOCATION	C17/PRISTANE RATIO	C18/PHYTANE RATIO
2016	A1G1 SURF PRE	2.22	1.69
2019	A2G1 SURF PRE	2.08	1.63
2022	A3G1 SURF PRE	2.26	1.69
2025	A4G2 SURF PRE	Not detected	Not detected
2028	A1G1 SURF POST	2.90	2.14
2031	A2G1 SURF POST	2.90	2.10
2034	A1G1 SURF P24	2.24	1.59
2037	A2G1 SURF P24	2.97	1.98
2038	A3G1 SURF P24	3.37	1.74
2043	A4G1 SURF P24	3.10	2.01
2050	A1G2 SURF P48	3.00	1.704
2053	A2G2 SURF P48	2.87	1.98
2056	A3G1 SURF P48	2.28	1.63
2059	A4G1 SURF P48	2.93	2.02
2062	A1G2 SURF P96	2.11	1.54
2065	A2G1 SURF P96	3.03	2.02
2072	A3G2 SURF P96	3.02	1.95
2075	A4G1 SURF P96	3.13	2.05
3503	Barge Oil	2.96	1.86

TABLE 2. C17/pristane and C18/phytane ratios by area for surface water samples.

SAMPLE ID	LOCATION	C17/PRISTANE RATIO	C18/PHYTANE RATIO
2017	A1G1 MIDW PRE	2.82	1.63
2020	A2G1 MIDW PRE	Not detected	1.93
2023	A3G2 MIDW PRE	2.30	2.53
2026	A4G1 MIDW PRE	Not detected	Not detected
2029	A1G3 MIDW POST	1.69	Not detected
2032	A2G3 MIDW POST	0.82	2.33
2035	A1G1 MIDW P24	Not detected	Not detected
2039	A2G2 MIDW P24	Not detected	Not detected
2041	A3G2 MIDW P24	Not detected	Not detected
2044	A4G2 MIDW P24	Not detected	Not detected
2051	A1G2 MIDW P48	Not detected	Not detected
2054	A2G2 MIDW P48	Not detected	Not detected
2057	A3G1 MIDW P48	Not detected	Not detected
2060	A4G2 MIDW P48	Not detected	Not detected
2063	A1G1 MIDW P96	Not detected	Not detected
2070	A2G2 MIDW P96	Not detected	Not detected
2073	A3G1 MIDW P96	Not detected	Not detected
2076	A4G2 MIDW P96	Not detected	Not detected
3503	Barge Oil	2.96	1.86

TABLE 3. C17/pristane and C18/phytane ratios by area for mid-water samples.

SAMPLE ID	LOCATION	C17/PRISTANE RATIO	C18/PHYTANE RATIO
2018	A1G3 MUD PRE	2.01	1.62
2021	A2G1 MUD PRE	2.67	1.46
2024	A3G2 MUD PRE	1.72	0.81
2027	A4G2 MUD PRE	3.35	1.44
2030	A1G1 MUD POST	2.29	1.42
2033	A2G3 MUD POST	2.93	1.73
2040	A2G2 MUD P24	1.69	1.68
2042	A3G2 MUD P24	1.80	1.34
2045	A4G1 MUD P24	4.08	1.37
2055	A2G2 MUD P48	1.88	1.55
2061	A4G1 MUD P48	2.80	1.40
2064	A1G1 MUD P96	2.11	1.67
2071	A2G2 MUD P96	1.68	1.51
2074	A3G1 MUD P96	1.87	1.51
2077	A4G2 MUD P96	2.52	1.44
3503	Barge Oil	2.96	1.06

TABLE 4. C17/pristane and C18/phytane ratios by area for bottom-water (mud) samples.

Illustrative gas chromatograms for *Apex* barge oil, surface-water samples and bottom-water samples are presented in Figures 1 and 2.⁷ The C17/pristane and C18/phytane ratios for surface-water samples and, separately, bottom-water samples are presented graphically in Figures 3 through 6 (the time scale represents nominal hours).

As seen in Table 2, except for one surface-water sample from a pretreatment control site (2025 A4G2 SURF PRE), oil fingerprinting by GC detected the target hydrocarbons in all surface-water samples. Pair-wise comparisons of the C17/pristane and C18/phytane ratios for pretreatment and 96-hour post-treatment surface-water samples using the Wilcoxon Signed Rank test indicated no significant difference between the groups at a significance level of 0.05 (which implies that the null hypothesis would not be rejected).⁸ The power of the test, however, is less than ten percent.⁹

GC analysis of mid-water samples found no detectable amount of hydrocarbons in the base fractions of P24, P48, and P96 samples (see Table 3). Variable hydrocarbon ratios were observed in the pretreatment mid-water samples.

⁷ In comparing sample chromatograms, differences in peak height ratios should be noted rather than differences in the absolute height of specific individual peaks. Differences in individual peak heights are only indicators of differences in the total amount of oil present in samples. Differences in peak height ratios, on the other hand, are indicators of differences in the relative concentration of oil constituents present in samples, which may be due to biodegradation.

⁸ Pair-wise comparisons test for statistical significance between the differences of paired groups of data. The Wilcoxon Signed Rank test is a distribution-free test for comparing samples (or paired groups) taken from two populations – in this case, treated and untreated contaminated sites – which may not be normally distributed. In performing comparisons, we assumed that each sample or paired group was independent of the other. The null hypothesis assumes that the samples were selected from identical populations.

⁹ The power of a test is a measure of the probability that the test will correctly reject the null hypothesis. Because the power of a test is directly related to the size of the sample population, and because the sample sizes for this analysis were very small ($n=4$), the power of the test is relatively low. The results of the test should therefore be viewed with discretion.

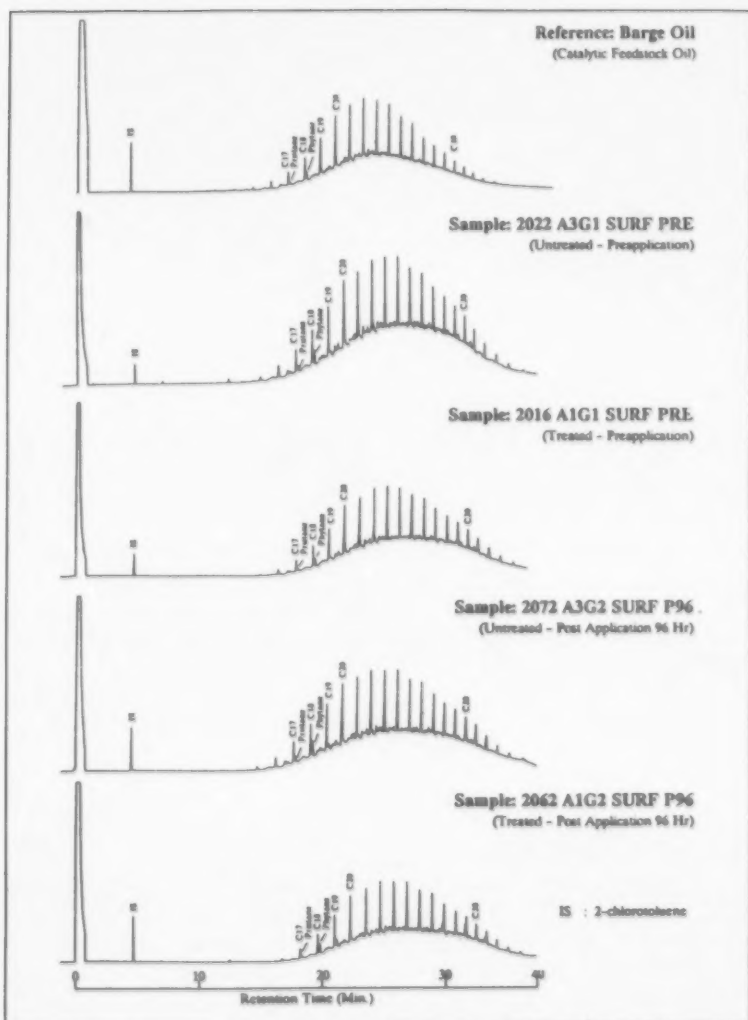


FIGURE 1. Gas chromatograms of Apex barge oil and surface water samples from treated and untreated sites just prior to and 96 hours after bioremediation agent application.

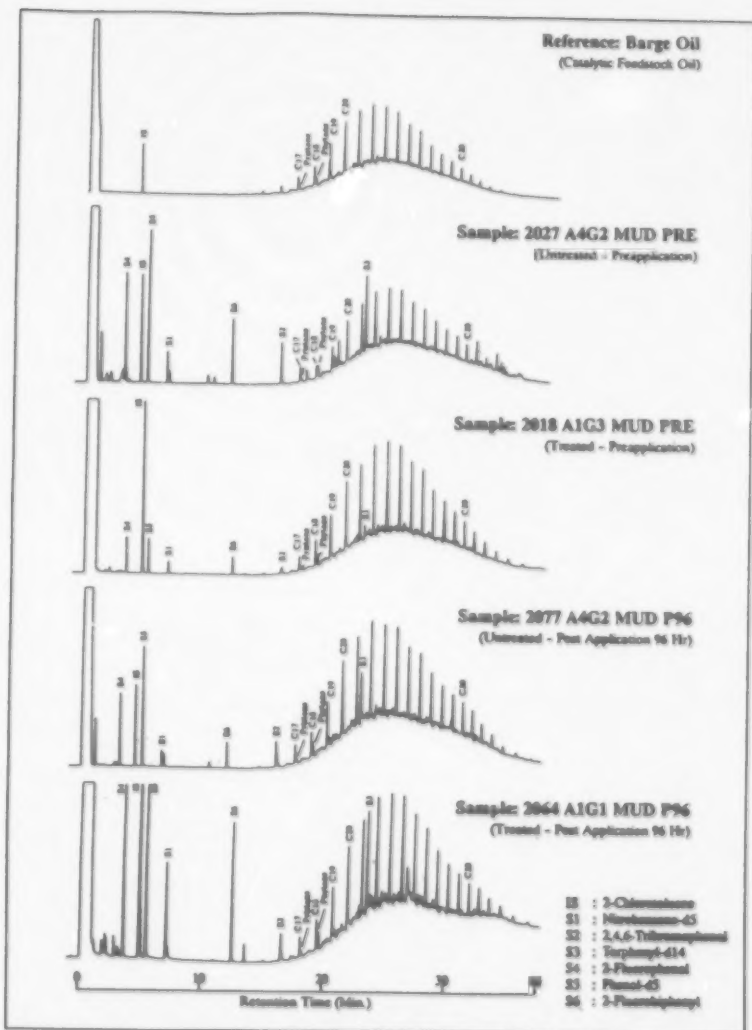


FIGURE 2. Gas chromatograms of Apex barge oil and bottom water (mud) samples from treated and untreated sites just prior to and 96 hours after bioremediation agent application.

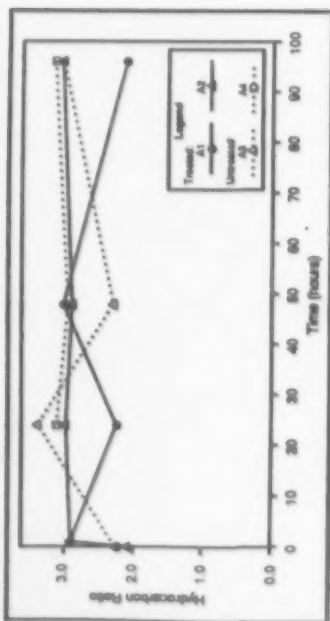


FIGURE 3. Plot of C17/pristine ratio for surface water samples from treated and untreated sites.

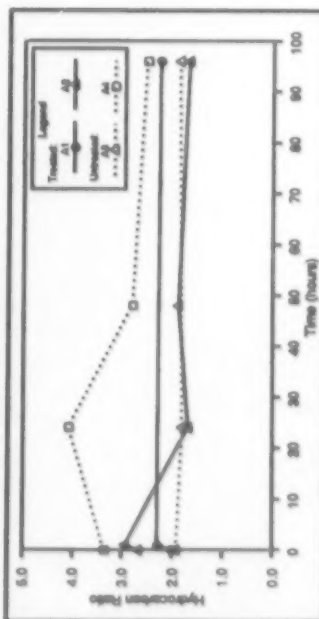


FIGURE 5. Plot of C17/pristine ratio for bottom water ("MUD") samples from treated and untreated sites.

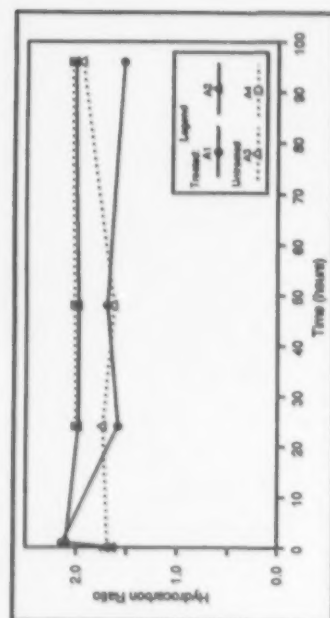


FIGURE 4. Plot of C18/phytane ratio for surface water samples from treated and untreated sites.

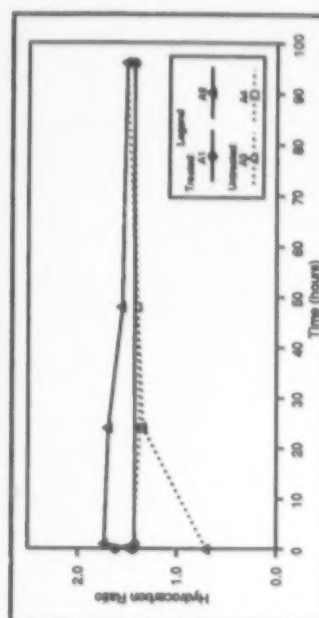


FIGURE 6. Plot of C18/phytane ratio for bottom water ("MUD") samples from treated and untreated sites.

The target hydrocarbons were detected in each of the mud samples analyzed, as seen in Table 4. Pair-wise comparisons of the C17 pristane and C18/phytane ratios for pretreatment and 96-hour post-treatment mud samples using the Wilcoxon Signed Rank test indicated no significant difference between the groups at a significance level of 0.05 (which implies that the null hypothesis would not be rejected). Again, however, the power of the test is less than ten percent.

Analyses of spiked blank and MS/MSD for C17 and C18 — performed to verify the efficiency of the BNA extraction method — demonstrated the following recoveries: 84 to 120 percent for analyses of water samples, with relative percent differences of 2 to 24 percent, and 86 to 93 percent for analyses of mud samples, with relative percent differences of 0 to 4 percent. These recoveries all are within acceptable limits.

Oil Fingerprinting by GC/MS

Results of GC/MS analyses did not identify any compounds atypical to the spilled oil. Atypical or unknown peaks that appeared in chromatograms were identified as straight-chain hydrocarbons.

Fatty-Acid Analysis by GC with Flame Ionization Detection

Small amounts (up to about 45 ug/ml) of what appeared to be fatty acids were detected in a few of the water fractions analyzed. The water fraction of one bottom-water sample collected from a treated site 24 hours after microbial agent application was shown to contain C3 through C10 fatty acids. Two other water fractions, one from a mid-water sample and the other from a mud sample, both collected prior to treatment, were determined to contain only one fatty acid each. In all the other water fractions, no fatty acids were detected. No fatty acids were detected in the mud fractions for the 0.2 g sample weights or the 1.0 g duplicates. Likewise, no fatty acids were detected in oil fractions for the 0.2 g sample weights. Duplicate analyses of the oil fractions using 1.0 g of sample each showed C3 or C4 fatty acids in five of twelve fractions. All five of these oil fractions were obtained from surface-water samples; four of the five samples were collected from treated sites.

Polynuclear Aromatic Hydrocarbons Analysis by GC/MS with Selected Ion Monitoring

High concentrations of phenanthrene, pyrene, chrysene and other PAHs were found in the barge oil. These compounds were also found in the pre-treated mud samples and the P96 mud samples, although at much lower concentrations. There is no obvious difference in the concentrations of these compounds, however, between the pretreatment and post-treatment samples.

Total Petroleum Hydrocarbon Analysis by Infrared Spectroscopy

No petroleum hydrocarbons were detected in mid-water samples. The highest concentrations of petroleum hydrocarbons were detected in mud samples. Overall, concentrations varied considerably between each sampling location for both surface-water and mud samples (from non-detectable to 203 mg/l in aqueous samples, to 40,100 mg/kg in mud samples) and between the various sampling time periods.

DISCUSSION

Alterations in Chemical Constituent Composition

The use of oil fingerprinting to assess alterations in the chemical constituent composition of oil is based on the biological degradation and physical weathering characteristics of various hydrocarbons. The general degradation pathways of hydrocarbons has been documented sufficiently in previous studies using mixed cultures,^{13,14,15,16,17} with the degradation of straight chain *n*-alkanes occurring foremost, followed by branched or cycloalkanes, aliphatic hydrocarbons and then by more complex higher molecular weight

hydrocarbon compounds (e.g., polynuclear aromatic hydrocarbons or PAHs). The actual rate of degradation is inversely related to the chain length of the compound, with the isoprenoids (e.g., pristane and phytane) being much more resistant to microbial attack than the straight chain (normal) alkanes.¹⁸

Because the isoprenoid compounds pristane and phytane have physical weathering characteristics very similar to the nearby straight chain compounds C17 and C18 but are more resistant to microbial utilization, ratios of these compounds (C17/pristane and C18/phytane) have been used historically to denote the degree of microbial degradation – a small ratio indicating that the diminution of the *n*-alkanes is likely to be due to factors other than weathering, volatilization, dissolution, photolysis, etc.¹⁹ That is, differences in relative levels of C17 and pristane or C18 and phytane in environmental samples over time, or compared to those for reference oils, can likely be attributed to biological degradation processes rather than physical weathering processes.

Surface-Water Samples

Figure 1 depicts the similarity in the chemical composition of the oil/water extracts from surface-water samples collected from the treated and untreated sites. The visible similarity in the peak distribution patterns indicates that the oil present in the samples collected from both the treated and untreated sites is the same (i.e., *Apex* barge oil).

The figure also depicts the similarity between the sample chromatograms and the chromatogram for the reference oil. Normally, based on the degradation pathway of hydrocarbons, the earlier eluting peaks in the sample chromatograms would be absent or diminished relative to the reference chromatogram as the rates of microbial utilization and volatilization are greater for these compounds than for later eluting, higher molecular weight hydrocarbons. Because the earlier eluting peaks as well as others are present in both the reference and sample chromatograms, simple examination of oil fingerprints does not indicate any large scale alteration due to microbial degradation.

For those surface-water samples that contained sufficient oil that could be characterized by gas chromatography, the C17/pristane ratios for samples collected from designated treatment sites just prior to agent application do not appear to differ significantly from the ratios for samples collected from the same sites 96 hours after treatment. (Refer back to Table 2 and Figure 3.) Likewise, the ratios obtained for samples from untreated sites do not appear to differ significantly for the same time periods. Statistical tests that would normally be used to compare these ratios, however, could not be used due to the paucity of data (i.e., in most cases, only two data points were available). In addition, the variability in the results among individual samples within and between sampling time periods tends to mask any trends that might otherwise be present. For example, over the 96-hour sampling period, the C17/pristane ratio ranged from 2.08 to 3.37, whereas the ratio for barge oil was 2.96.

Few degrees of freedom and some variability in analysis results also prevent reliable statistical comparison of the C18/phytane ratios for surface-water samples. For instance, over the 96-hour sampling period, the C18/phytane ratio ranged from 1.54 to 2.14, whereas the ratio for barge oil was 1.86. Visual inspection of these data, however, do not give the indication of any detectable change due to biodegradation at either the treated or untreated sites within the 96-hour sampling period (see Figure 4).

In NOAA's study by Mearns on the *Apex* spill bioremediation activity, pre-application surface oil samples collected 3 to 5 days prior to the application of the biocide had C18/phytane ratios that ranged from 2.1 to 2.2. Surface oil samples collected two days following the application had ratios that ranged from 1.8 to 2.2. Again, the number of samples collected were insufficient to perform the appropriate statistical tests that would discern any significant differences.²⁰

In the recent bioremediation studies conducted in Alaska following the *Exxon Valdez* oil spill, the C18/phytane ratio was used to denote biodegradation during the summer of 1989

in an oiled cobble beach that had been treated with an oleophilic fertilizer.²¹ Over a four week period, this ratio decreased by 70 percent, attributable to microbial activity. Although a significant decrease in the C18/phytane ratio was noted, a wide range in the C18/phytane values also was observed.

Looking back at Figures 3 and 4, it is interesting to note the obvious increase in both ratios for surface-water samples from treated sites (A1 and A2) within the first hour after application of the bioadditive. This increase would seem to reflect the presence of residual hydrocarbons in the bioadditive (or a rapid alteration in the composition of the oil). Because an analysis of the bioadditive was not performed, however, this inference cannot be supported by the analytical results.

Bottom-Water (Mud) Samples

As seen in Figure 2, visual examination of the chromatograms for bottom-water or mud extracts reveals the same basic pattern of peaks for samples collected from both treated and untreated sites, regardless of the sampling time. That is, the oil present in sediments in the treated sites 96 hours after agent application does not appear significantly different from that in the sediments prior to application. The figure also shows that the oil in sediments from treated and untreated areas is similar to the reference oil. The earlier eluting hydrocarbons (e.g., intermediate molecular weight alkanes) present in the reference oil are still quite obvious in both the treated and untreated samples, even at the 96-hour sampling time. These results imply that there was no significant biodegradation of the oil in treated or untreated sites over the 96-hour sampling period.

Degradation Products and Intermediates

The breakdown products of microbiological degradation of hydrocarbons are fairly well known from laboratory studies.^{22,23} These studies have shown that fatty acids are produced as some of the first breakdown products of alkanes through the process of carboxylation followed by β -oxidation.^{24,25} Nevertheless, fatty-acid production has not been examined extensively in any of the documented bioremediation field studies probably for a number reasons, including their high biodegradability and their relatively high solubility which results in their rapid dilution, dispersion, and eventual biological uptake. Generally, analysis for fatty acids as a group in environmental samples is not performed because these compounds are not thought to present any threat to the environment. The decision to analyze for fatty acids in the *Aper* spill samples was based on product information supplied by the bioadditive vendor and knowledge of fatty-acid production coincident with biodegradation, as mentioned above.

The initial metabolic mechanism of alkane degradation to produce fatty acids is as follows:



As the mechanism proceeds, two-carbon fragments are split off, resulting in a gradual shortening of the aliphatic fatty-acid chain. In the early stages of microbial degradation of spilled oil, therefore, the fatty acid derivative of the alkanes present in the oil would likely be formed, with subsequent steps in the oxidation process producing aliphatic acids with fewer number of carbons. Because the oil from the barge consisted primarily of straight chain alkanes C15 to C30 in carbon number (evidenced in the oil fingerprint analyses), production of C3 to C10 fatty acids would have been expected from the biodegradation of intermediate molecular weight *n*-alkanes present in the spilled oil. Nevertheless, none of the 53 surface-water, mid-water, and bottom-water (mud) samples analyzed contained detectable levels (greater than 3 ppm) of any positively identified fatty acids in the C3 to C10 range.

Originally, the supposition was that the rate of oil degradation — implied by the bioadditive vendor to be such that a 48 to 99 percent decrease in the concentration of oil would occur within 24 hours²⁷ — would result in detectable levels of fatty acids, at least in

total if not singularly. Not having detected these compounds at levels above 3 ppm may indicate that they were not present in the samples. Alternatively, they may have been present in amounts too low for detection.

SYNOPSIS AND CONCLUSIONS

The results from each of the distinct analytical procedures described above would not singularly be sufficient to judge the efficacy of the bioremediation program conducted in Marrow Marsh following the *Aper* barges incident. Taken together, however, the results from each of these analyses seem to support and, in some cases, reinforce the same general conclusion. The similarity of each of the gas chromatograms to the reference oil for both surface-water and sediment samples indicates that little or no alteration of the oil occurred over the 96-hour sampling period, even though alkanes, in particular, are supposed to rapidly degrade in sediments.²⁸ The lack of any significant change in the C17/pristane and C18/phytane ratios just prior to and 96 hours after bioadditive application, taking into consideration results variability among samples, also is indicative of little change taking place in the constituents of the spilled oil. Lastly, the absence of detectable fatty acids, which have been documented as being among the first intermediary products of microbial utilization of hydrocarbons (*n*-alkanes in particular), is supportive evidence that little or no detectable microbial activity took place during the 96-hour sampling period.

Despite the apparent strength of the results, certain questions still remain:

- *Were the analytical procedures used technically insufficient to detect any biodegradation that actually might have occurred?* Given the restraint that biological parameters, such as Most Probable Number (MPN) – cells per unit volume – and respirometry, could not be employed to assess microbial activity due to the frozen condition of the samples, only the specific analytical chemical procedures described previously could be performed to evaluate the efficacy of bioremediation treatment in Marrow Marsh. In addition, it is possible that the fatty-acid analysis was inappropriate as an indicator of oil degradation because it may have lacked the sensitivity to detect the fatty-acid levels present. These constraints may lend doubt to the conclusiveness of the analyses performed, particularly because microbial growth and activity response parameters are recognized as being essential for properly characterizing the dynamics of hydrocarbon utilization from a bioremediation effort.
- *Why were the results from the treated and untreated sample sites so similar?* The reason for this similarity cannot be easily ascertained through the data presented in this report. One possible explanation is that the mechanism that was affecting (or inhibiting) the alteration of *n*-alkanes was present in both areas. Another, especially evident for certain parameters (i.e., C18/phytane and C17/pristane ratios and total petroleum hydrocarbons), is that the samples collected from each site varied enough that any differences in these parameters may have been masked. For instance, data analysis using the Wilcoxon Signed Rank test did not discern significant differences in the C17/pristane and C18/phytane ratios between treated and untreated sites. Another explanation may be that the distance between and methods to sequester treated and untreated sites was not sufficient to prevent mixing, taking tidal flushing rates in the marsh into account.
- *Were the number of samples taken insufficient to allow for detection of microbial degradation?* The number of samples collected turned out to be too few to characterize adequately the variability that was observed among samples from treated and untreated sites. Had more samples been taken and analyzed, the power of the statistical tests employed would have been greatly enhanced and any differences among treated and untreated samples, if any, could have been better evaluated. Generally, this analysis would have benefited had the design of the sampling program considered the requirements of the analytical methods that were to be employed for analyzing samples and provided for collection of more samples at each sampling site and water depth. Concomitantly, it probably was not necessary to sample as many

time intervals within the initial period after application of the bioremediation agents; a pre-application sampling followed by another a week later would probably have been sufficient.

- *Was the sampling period inadequate to document microbial degradation of the spilled oil?* Perhaps the 96-hour sampling period was too short to document the overall efficacy of the bioremediation program, particularly in light of findings that microorganisms generally require an adaptation period of hours to several days before beginning to grow and reproduce.²⁹ Notwithstanding, the sampling program used in Galveston Bay was designed by the RRT Ad Hoc Task Force using state of knowledge information and data supplied by the bioadditive vendor.

Obviously, all of the above discussion should stimulate oil spill response managers to realize the pitfalls associated with monitoring programs developed in the atmosphere of an on-going spill. If anything, we hope this article has illuminated some of the vagaries and technical problems associated with a field-effort developed in a very short time frame. For future bioremediation activities, emphasis should be placed on measuring only those parameters that have been determined to be appropriate through previous efficacy tests or protocols. In addition, post application monitoring should be designed to determine efficacy as affected by the particular environmental conditions of the application area, including provisions for representative and statistically sound sampling.

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Tainting by Short-Term Exposure of Atlantic Salmon to Water Soluble Petroleum Hydrocarbons

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The value of marine salmonids for 1991 on the Pacific coast of Canada is estimated at 100 million dollars and on the Atlantic coast total is at least 85 million dollars (Cook, 1992). This industry competes in a world market where a "clean" image is a potent force. Among the adverse image problems is flavor "tainting" in the context of petroleum contamination. For decades the marine fishing industry quality indices often listed "bilgy" as the worst category and this included the potential for post-harvest fuel oil contamination.

Mariculture activities are almost always conducted along shorelines where even normal vessel activity can contribute to low-level pollution (Paradis and Ackman, 1977), although point sources of on-shore contamination (e.g. Ackman and Noble, 1973) could also lead to hydrocarbon input through drainage systems to inlets with salmon seacages. The ultimate acute hazard is of course an onshore tanker disaster, but any marine accident can contribute significant amounts of water soluble petroleum hydrocarbon to the water occupied by seacage salmon. These spills are almost always thought of in terms of crude petroleum or heavy bunker fuels, since the resulting surface slicks or mousses are featured by the media. The real fish or shellfish "tainting" is done by the water soluble hydrocarbon fraction which in fact closely resembles the aromatic hydrocarbons of No. 2 diesel or domestic furnace oil fuels (Newton et al., 1991), so these components are the crux of the matter.

A list of seafood safety problems (Anon, 1991a) only touches on health effects in terms of "presence of significant levels of undesirable chemicals (causing acute or chronic effects) in edible fish or shellfish tissue derived from the natural environment or of anthropogenic origin, and the subject is not really covered by Canadian publications on the environment listed by Environment Canada (1991b). There are however ongoing concerns about certain polycyclic aromatic hydrocarbons as chronic or persistent potential carcinogens, (Geachan et al., 1991), and methods have been designed to determine these materials in fish tissues (Lebo et al., 1991). "Tainting" in the context of this report refers to the "development of an atypical flavor or odour in the edible tissue of finfish and shellfish caused by natural spoilage or by the assimilation of contaminants into the tissue" (Ernst et al., 1989), and in this report is not to related safety issues of the toxin or bacterial spoilage type.

Our prior experience in exposing finfish (Ernst et al., 1987) and scallops (Ernst et al., 1989) to the water soluble fraction (WSF) of crude petroleum hydrocarbons showed that lean ($\leq 1\%$ fat) fish or shellfish muscle could be tainted through picking up a range of aromatic hydrocarbon from benzene to approximately the methyl naphthalenes. They could also be depurated (freed of the resulting objectionable hydrocarbon flavors) by holding for a few days in clean seawater. Farmed Atlantic salmon commonly have 12-15% of muscle fat and information on the uptake of hydrocarbon, their potential storage in adipocytes, and rate of depuration is apparently lacking.

In effect this is a preliminary report primarily looking at Atlantic salmon and hydrocarbons from the consumer viewpoint, and not from the more usual views of chronic or acute toxicity. The experiment was however basically also intended to establish working ranges for exposure of salmon in seawater to WSF hydrocarbons and for future definitive exposure and depuration studies.

Materials and Exposures

Esso Petroleum Canada provided Flotta North Sea crude petroleum. This was stirred with cold seawater (1:299 v/v ratio) for 24 hours in a stainless steel vessel cooled to 5-8°C. After settling for 48 hours this provided a stock solution for dilution with fresh cold seawater to appropriate exposure levels (targeted as 0.5, 1.0 and 1.5 ppm WSF hydrocarbons). Well-oxygenated seawater at a flow of 250 ml/min was provided, fed into three 355 L fibreglass tanks with clear plastic covers. Three salmon (average weight 367 g) was placed in each tank for exposure and a control group was kept in clean seawater. Over the early part of six hours the WSF hydrocarbons was determined to actually be 0.45, 0.87 and 1.54 ppm by the Murray extraction procedure (Murray 1979, Murray et al., 1984) with correction factors established earlier (Ernst et al., 1989). The level dropped by half in the later stages of exposure. The WSF stock solution was prepared at TUNS and the exposures were conducted in the Aquatron facilities of Dalhousie University.

Fish Analyses

The fish were killed by a blow on the head, washed and transported to TUNS in individual plastic trays. In the TUNS Department of Food Science and Technology the fish were immediately gutted, skinned, filleted and frozen in polyethylene bags at -35°C until required for sensory evaluation or other analyses.

The steam distillation technique of Ackman and Noble (1972), recently reinvented by Newton et al., (1991), was applied with recovery corrections based on a mixture of eight hydrocarbons. These were dissolved in ethanol and injected by syringe (1 ml) into 50 g of salmon fillets. After a diffusion period of 1 hour the flesh was minced and steam distilled. Gas chromatography was performed on a DB-1 column (60 m X 0.25 mm) in a Perkin Elmer 8420 GC with FID. The internal standard n-heneicosane was coinjected. Fillet lipid was recovered by the Bligh and Dyer (1959) procedure and the weight percentages of triglycerides and phospholipid were determined by TLC-FID (Chromarod-latroscan, Ohshima and Ackman, 1991).

Sensory Panels

Sensory panellists were experienced with petroleum in shellfish and were drawn from the students and staff of the C.I.F.T. Salmon flesh was minced in a Cuisinart food processor, covered in a glass dish and cooked in a microwave. Preferences were ranked among the four samples (three exposed, one control) by customary technique.

Results and Discussion

Figure 1 is a gas chromatogram of hydrocarbons recovered from WSF concentrate (stock solution). The n-alkanes were virtually absent and the probable impact of toluene, xylenes, ethylbenzene and other alkylated benzenes can be forecast from even the off-scale peaks. Polynuclear aromatics higher than the methyl naphthalenes were virtually absent. There were no fish mortalities or obvious distress over the 6 hour exposure period. Panellists could rank the fish exposed to the levels of 0.45 ppm and the two higher concentrates correctly to a significance of 1% and between the levels of 0.87 and 1.54 ppm correctly to 5%. They were not always anxious to participate in repeat taste panels! Control fish had about 1 ppm of total hydrocarbons, primarily n-alkanes (compare Pacific salmon examined by Sasaki et al., 1991; these fish presumably acquired many hydrocarbons from natural food sources). The muscle accumulations of total hydrocarbons could in trial fish be ranked in accord with sea-water concentrations and were 13.5 ppm, 25.6 ppm and 31.3 ppm, with the concentration factors shown in Figure 2. Clearly, the threshold for taint can be inferred to be less than 0.45 ppm of WSF. The muscle lipid in these small salmon was 4%, compared to 1% or less in cod. Ernst et al (1989) found that hydrocarbon transferred into cod muscle from 1.38 ppm of WSF was not detected. In their study an 8 hour exposure to 3 ppm WSF gave a muscle accumulation of 0.7 ppm hydrocarbons. It is felt that there would be 100 times as much triglyceride in the salmon muscle as in the cod muscle, thus providing ample hydrocarbon uptake and storage sites, but depuration was not attempted. It is however generally accepted that the more fat in a tissue, the greater the potential for uptake and storage (Hardy et al., 1974; Whittle and Mackie, 1971; Whittle et al., 1977). Commercial farmed salmon had as much as 14% fat in the muscle, and whether depuration is readily possible in such fatty fish will be the subject of our ongoing research supported by a Strategic Grant from NSERC.

Acknowledgement

Sensory panel studies were conducted by E.J. Macpherson.

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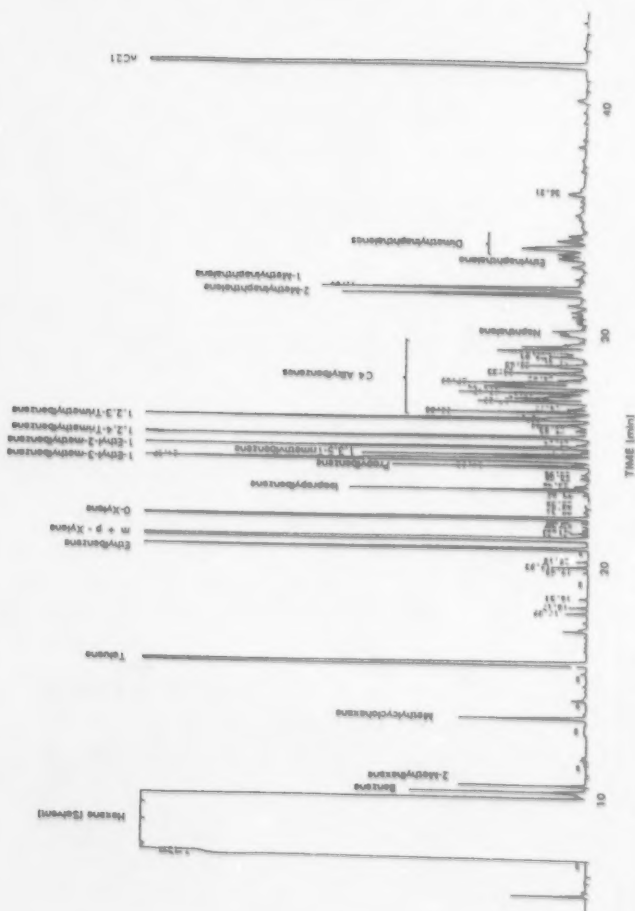


Figure 1.

Typical gas chromatogram of the WSF of Flotta crude oil used in exposure studies with salmon. Heneicosane (C21) was used as an internal standard. Note that benzene and 2-methylhexane are recorded with an attenuation 2-fold less than the rest of the chromatogram. C4 Alkylbenzenes = several tetramethyl- and propyl-methyl-benzenes.

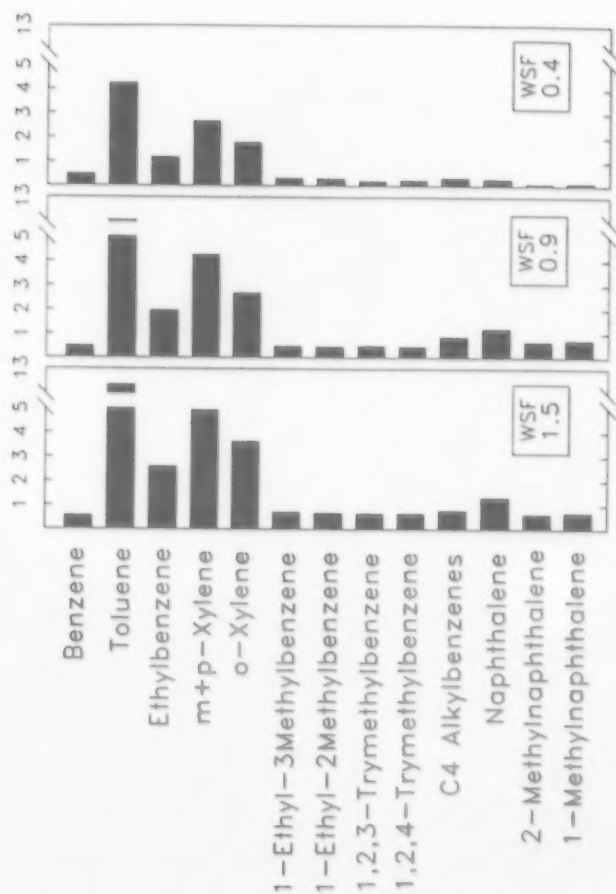


Figure 2. Major aromatics in salmon muscle [ppm].
C4 Alkylbenzenes = several tetramethyl- and propyl-methyl-benzenes.

Field and experimental tainting of arctic freshwater fish by crude and refined petroleum products

by

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Abstract

We have investigated two incidences of tainting of northern fish: one by effluent from a synthetic crude oil production plant on the Athabasca river, and one by diesel fuel spilled when a truck overturned near the Cameron River, N.W.T. These cases both resulted in complaints that downstream populations of whitefish were tainted with an oily taste. In both of these instances supplies of the spilled material were available, and laboratory exposures of fish confirmed the ability of the spilled materials to produce taints in fish. These confirmatory experiments lead to a more systematic study of the relationship between exposure of fish to oil in the water and sensory responses of taste panels. Fish (rainbow trout and arctic char) were exposed to three mixtures of Norman Wells oil (nominally 3, 12 and 50 ppm) in water over a period of seventy-two hours, and then transferred to clean holding tanks where they were held for a further 600-840 hours. Three fish were removed from each tank at intervals over both uptake and clearance phases so that we could estimate rates of the production and clearance of the oily taste. Taste panel members were selected for their ability to detect, identify and rank correctly weak oil solutions. All panellists were able to discriminate between treated and untreated fish during the uptake (mostly by the earliest sampling period of four hours) and early clearance phases some panellists continued to detect tainting in the fish even by end of the clearance phase 600-840 hours after fish had been transferred to clean water. The implication of these taste panel results is that oil tainting is sensitive to dosage of oil, duration of exposure, and duration of post-exposure time in clean water. Arctic char can be expected to become tainted after an exposure of only a few hours, and to remain tainted for over a month following cessation of exposure.

Introduction

In February, 1982, a spill occurred at the Suncor oil sand extraction plant near Fort McMurray, Alberta, releasing effluent from the plant into the Athabasca River. Following the spill complaints were received that whitefish from the downstream winter fishery had become tainted. Investigation confirmed the complaints and resulted in closure of the fishery for the balance of the season. In the laboratory, lake whitefish (*Coregonus clupeaformis*) were exposed experimentally to Suncor effluent and then fillets were examined by sensory panels to confirm petroleum tainting.

A second very similar complaint was received following a spill of diesel oil into the Cameron River, near Yellowknife, N.W.T. in March,

1983. In this instance also whitefish were exposed in laboratory tests and the ability of the diesel to produce tainting in fish was confirmed. Both this and the Suncor example above resulted in convictions under the Fisheries Act.

The published literature has documented numerous examples of tainting of fish and other aquatic organisms by petroleum products. Tidmarsh et al (1986) gave several pages of references in which tainting of fish and other fishery products by petroleum products was reported. Following these field incidences, we began more systematic experimental exposures of rainbow trout and arctic charr to define the dosage-tainting relationships. Arctic charr (*Salvelinus alpinus*) and rainbow trout (*Oncorhynchus mykiss*) were exposed to Norman Wells crude oil in studies to describe the production and retention of petroleum-induced off-flavours under laboratory conditions. These experimental tests are described below.

Methods

Experimental tests with whitefish showed that exposure to diesel fuel for as little as four hours was sufficient to produce a noticeable off-flavour in the fish (York et al, unpublished). The fish used in these experiments were Rockwood Hatchery brood stock. The arctic charr were raised from eggs obtained in 1977 from Nauyuk Lake, Northwest Territories. Their mean weights and lengths were 729.1 ± 109.2 g and 40.6 ± 2.1 cm respectively. The rainbow trout were from the Tagwerker strain with mean weights and mean lengths of 943 ± 189 g and 41.9 ± 2.7 cm respectively. All the fish were starved 14 days prior to treatments with oil, and were not fed during the uptake or the clearance phases of the experiments. All the fish tanks were covered with black polyethylene producing a 0 hour photo-period for the entire experiment. Water temperatures in the rainbow trout and arctic charr exposures were $10.2 \pm 0.9^\circ\text{C}$ and $9.1 \pm 0.3^\circ\text{C}$ respectively; dissolved oxygen ranged from 6.2 - 9.5 ppm and 5.6 - 9.3 ppm. At the end of the 72-hour exposures fish were transferred to clean tanks with water flow rates of 20 L min^{-1} which maintained oxygen levels at 9.5 ppm for the entire clearance phase.

Twenty-two arctic charr were placed in each of four 770-L circular tanks for the 72-hour exposure phase. One tank was untreated and three tanks were treated with varying concentrations of Norman Wells crude oil (50, 21, 3 ppm oil:water). After 72 hours the fish were transferred to clearance tanks. Similarly, twenty-four rainbow trout were placed in each of the four exposure tanks for the exposure phase and then transferred to clean water after 72 h.

Because fish of this size and number would exhaust all the dissolved oxygen in their tank; in 3 hours, and because aeration would volatilize off most of the crude oil water soluble fraction, a flow-through dosing apparatus had to be devised that would maintain acceptable oxygen levels, and keep crude oil concentrations constant throughout the experiment. The dosing and mixing apparatus used was a 20 litre header tank suspended 5 feet above each fish tank. Four litres per minute of dechlorinated City of Winnipeg tap water were mixed with the required volumes of crude oil which was added using a

Harvard Apparatus Model 1201 Peristaltic Pump. The water and oil were rapidly mixed in each header tank by means of large magnetic stirrers and stirring bars. Swing arms located at the bottom of each tank dispensed the mixture by gravity, preventing any oil which accumulated at the water surface of the tank from being dispensed into the fish tanks. Flow rates of water and oil were monitored regularly throughout the exposure period and the total volumes dispensed to each tank were recorded and used in determining the final oil : water ratios. The water in each fish tank was circulated with a submersible pump to aid mixing. At times of 4, 24, 48, and 72 hours in the uptake phase and 24, 288, 600 (charr) and 840 hours (trout) in the clearance phase, three fish were sampled from each of the 4 exposure tanks.

Following removal from the experimental tanks, fish were weighed, measured, sexed, and filleted; washed fillets were vacuum-sealed individually in 1-mil polyethylene - mylar laminated poaches, coded, and stored at -35 C until sensory analysis. Ten panel members experienced in the evaluation of fish products were selected according to their ability to perceive hydrocarbon off-flavours in five water solutions, and to rank those solutions in the correct order of concentration. The solution was prepared from dilutions of the water soluble fraction (WSF) of Norman Wells crude oil. The rating procedure was a modification of quantitative descriptive analysis (Stone, et al 1974), where a 15-cm line was provided with end points marked weak and strong. Panellists were asked to record their response to each liquid cocktail by placing a mark on the line at a point corresponding to their perceived intensity of any petroleum off-flavour in the sample. Responses were then converted to numerical scores with a template marked in mm.

For the taste panels fish samples were prepared daily. The vacuum-packed fillets were thawed in cold running water, removed from the poaches, and chopped into 1/4-inch cubes. The pieces were mixed and seven gram portions were wrapped in aluminum foil and numerically coded for identification during sensory analysis. The taste panels were run, with minor variation, according to prescribed methods (Iredale and York, 1976). For presentation to panellists, the wrapped coded samples were cooked over steam for five minutes, randomly placed on warming trays, and presented to panellists in a sensory-testing laboratory equipped with individual booths. Panellists were instructed to chew unsalted soda crackers and to rinse thoroughly with tap water between each sample, to minimize off-flavours from one sample to another.

Results

Sensory panel scores for arctic charr fillets during the uptake phase are shown in Figure 1. The intensity of taint detected by the judges was directly related to the nominal concentration of oil added to the exposure water at all sampling times. Exposure for as little four hours resulted in dosage-dependant tainting; the control value at that time was 1.7 while the treatment groups ranged from 4.5 to 32.2. The intensity of tainting continued to increase over the subsequent sampling interval between four and twenty-four hours, the maximum value attained by then being 51.5 in the 50-ppm group. There was little further change during the continued exposure from twenty-four

to seventy-two hours, with the maximum value for the 50-ppm group increasing to only 53.8. This failure to increase over the final two exposure periods suggests that an equilibrium had been established between fish and tainting substances within about twenty-four hours.

Following transfer to clean flowing water, the charr from treatment groups all showed a decline in the intensity to taint over sampling periods as long as 600 h after the transfer (Figure 2). The 50-ppm treatment group declined from a mean tainting score of 53.8 at the time of transfer to 19.2 at 600 hours. However, the lowest treatment group declined proportionately less, from 12.6 to 8.9. All treatment groups were still scored higher than untreated controls throughout the clearance phase.

Tainting of rainbow trout during the uptake phase is plotted in Figure 3. The time-course of taint production was very similar to that observed with arctic charr, and the final values reached were about the same. Again there was a clear relationship between nominal dosage and tainting intensity. The highest dosage (50 ppm) had reached essentially the same level of tainting by 24 h as subsequent sampling times, but the 12 ppm group tended to increase almost linearly from 4 to 72 h, with little indication of the plateau shape typical of the other doses with both species.

Loss of taint by the rainbow trout following removal to clean, flowing water is shown in Figure 4. Trout from the two higher dosages clearly lost tainting intensity over the clearance phase, especially during the first 24 h, during which the 50-ppm group fell from a score of 51.2 to 38.9 and the 12-ppm group fell from 34.8 to 25.8. In contrast, the lowest treatment group (3 ppm) remained relatively constant, dropping only from 18.8 to 12.5 over the entire clearance period of 840 h.

These results indicate empirically that the threshold for tainting is below a nominal exposure of 3 ppm, and that the incorporation of tainting substances can occur in less than four hours. Tainting substances were cleared rapidly during the first 24 h after to clean water, and more slowly after that. Charr and responded very similarly to both uptake and clearance phases, with

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Figure 1. Tainting of arctic charr by Norman Wells oil

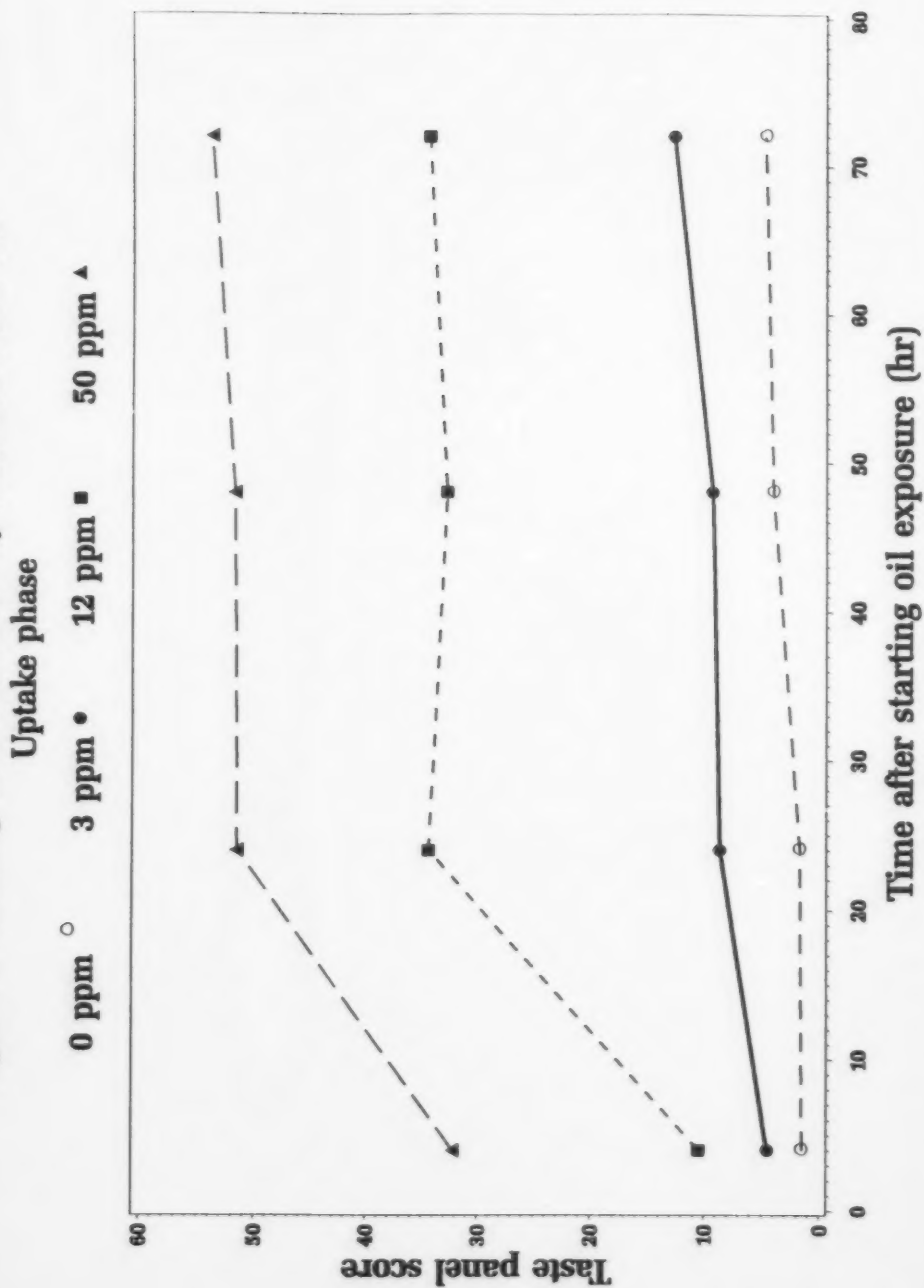


Figure 2. Timing of taste change by normal taste

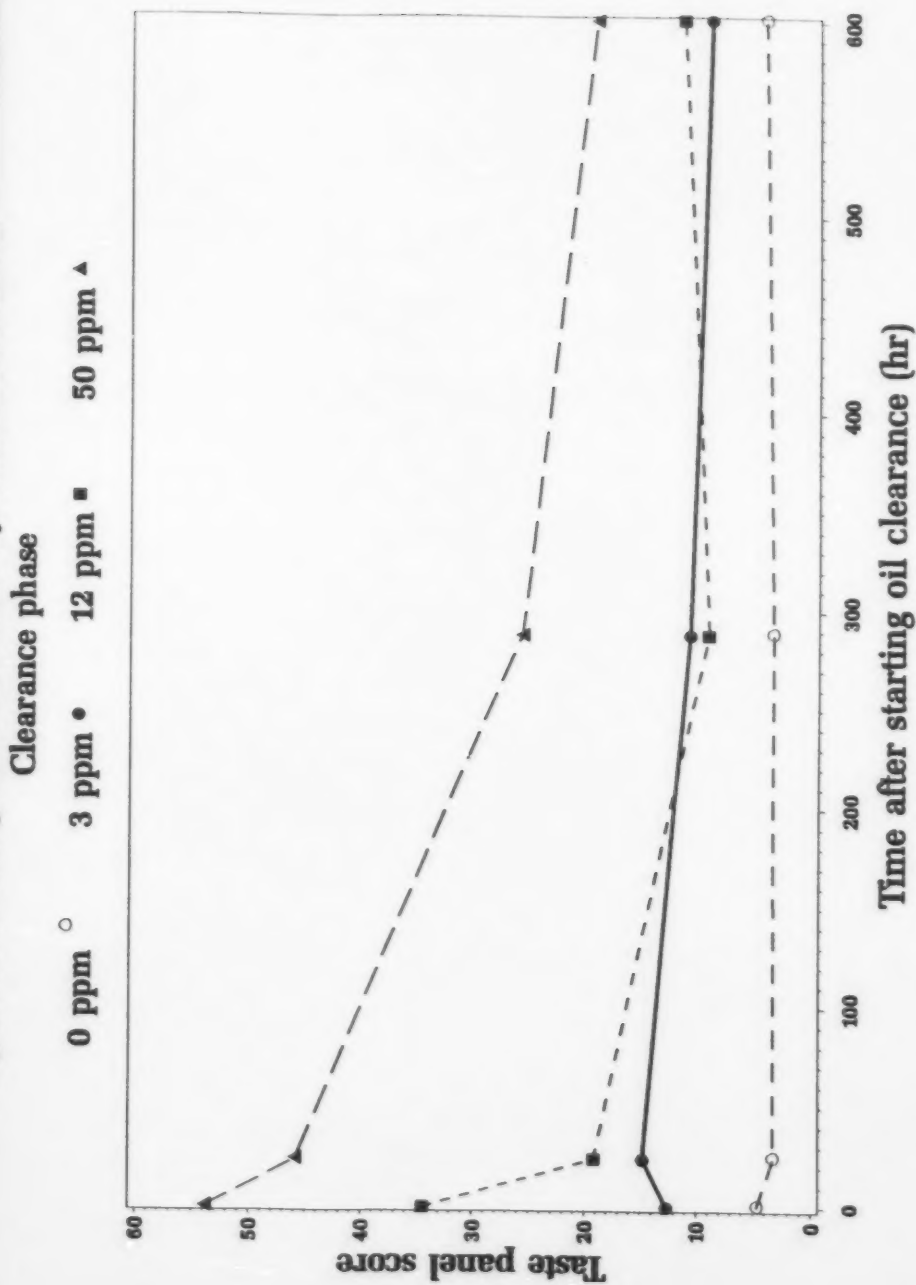


Figure 3. Tainting of rainbow trout by Norman Wells oil

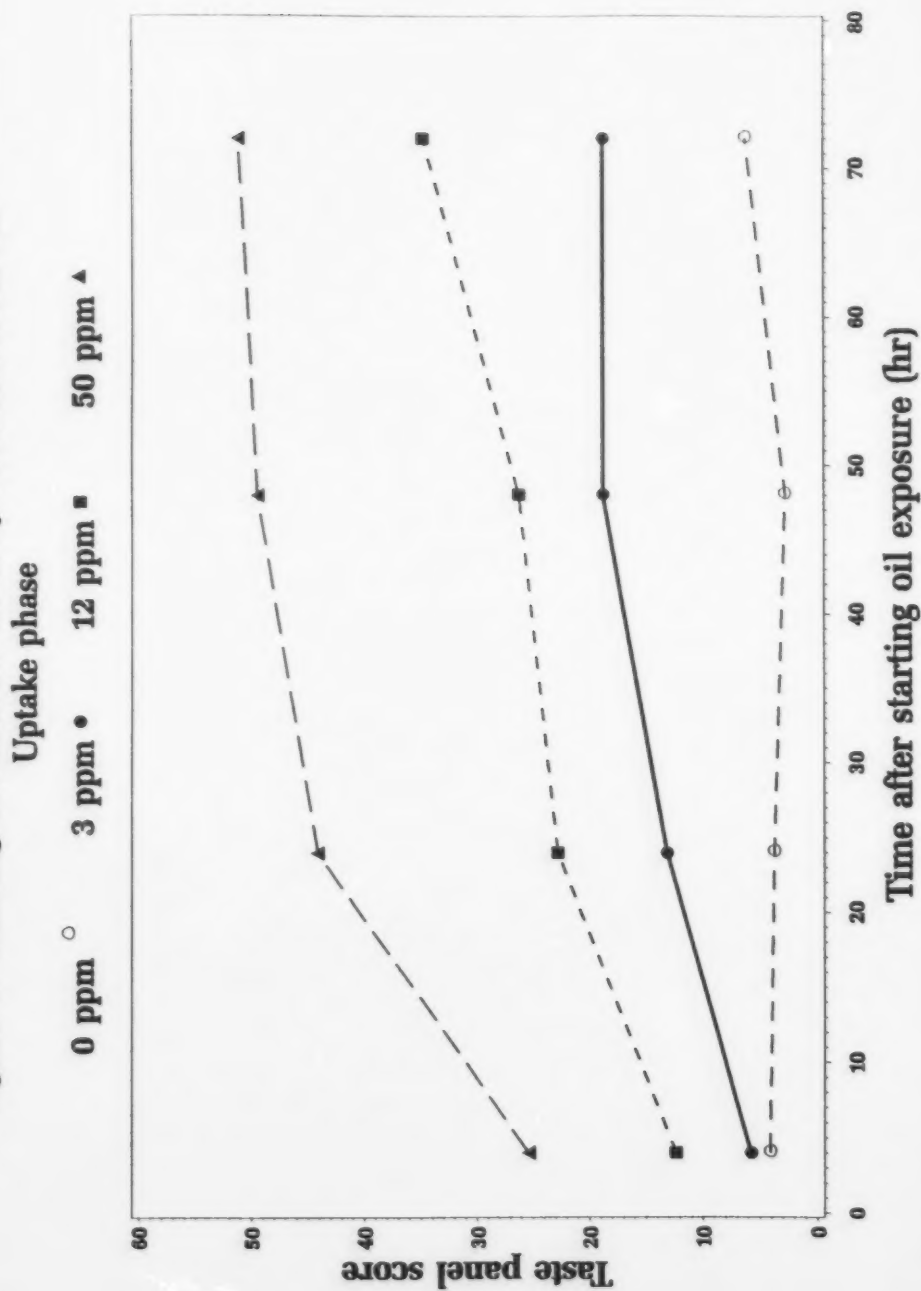
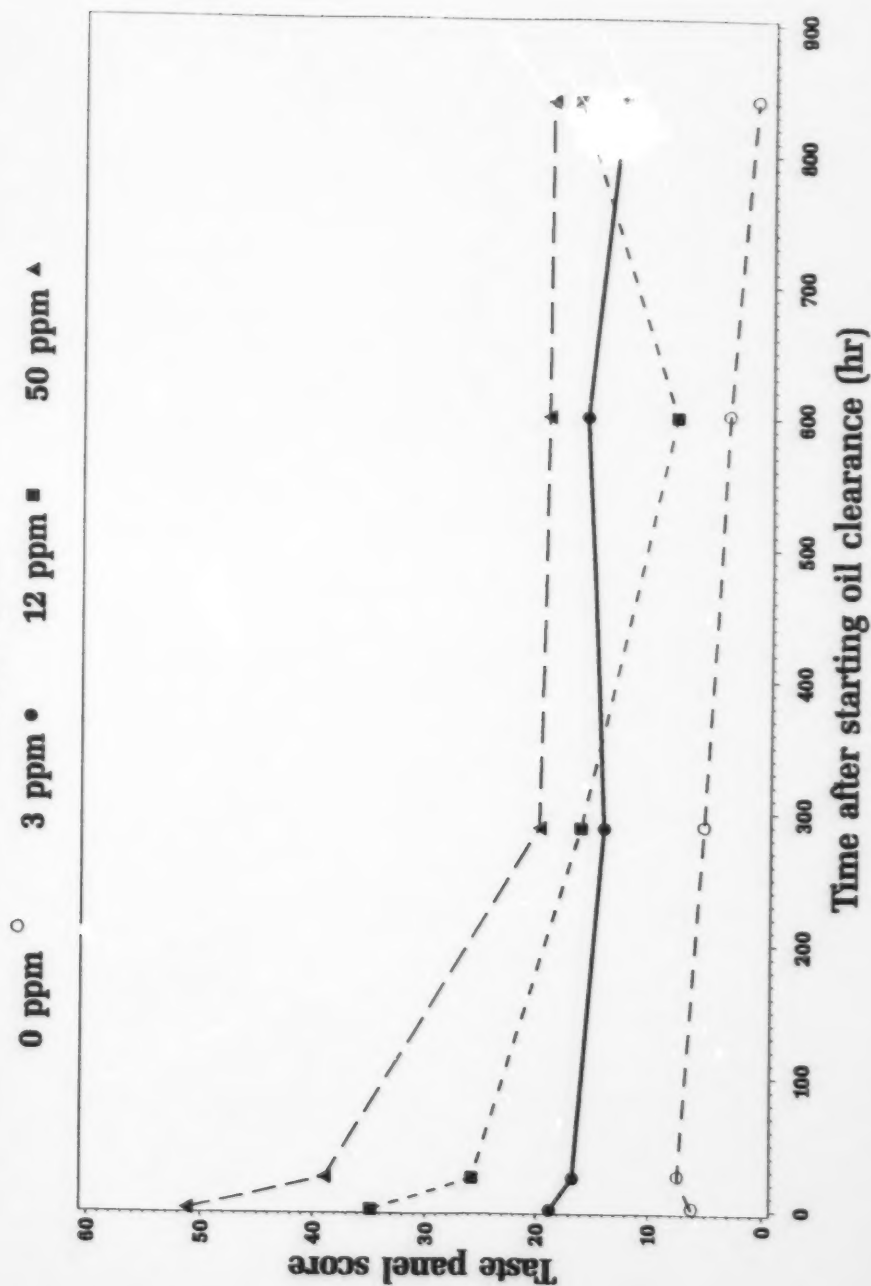


Figure 4. Tanning of rainbow trout by Norman Wells oil
Clearance phase



WILDLIFE RESPONSE ON THE ALASKAN NORTH SLOPE**by Donald Costanzo and Bruce McKenzie****Alaska Clean Seas****12350 Industry Way, Suite 200****Anchorage, AK 99515****ABSTRACT**

Recognizing the need for a comprehensive plan to deal with potentially oiled wildlife on the Alaskan North Slope, Alaska Clean Seas (ACS)¹ developed and implemented a multi-faceted wildlife protection strategy during 1991. The strategy incorporated all aspects of wildlife response including protection of critical habitat, hazing, capture and stabilization, long term rehabilitation, and release. Implementation of the strategy included the development of specialized training, the procurement of equipment, and the construction of a bird stabilization center. The result of this initiative is a comprehensive wildlife response capability on the Alaskan North Slope.

INTRODUCTION

One of the most visible components of spill response is the protection of wildlife. Recognizing the need for a comprehensive plan to deal with potentially oiled wildlife on the North Slope, ACS and its member companies worked in collegium with federal, state and local governments to develop a wildlife protection strategy.

In November 1990 a joint industry/government Wildlife Task Force was formed to develop a protection strategy for wildlife in a spill event on the North Slope of Alaska. Task Force members included; U.S. Department of Interior, Alaska Department of Fish and Game, North Slope Borough, ARCO Alaska Inc., Alyeska Pipeline Service Co., BP Exploration (Alaska) and Alaska Clean Seas.

¹ Alaska Clean Seas is the oil spill response cooperative for Alaska's North Slope oil exploration, production, and pipeline operations as well as Alaska Arctic Regions offshore exploration activities. Current members of the cooperative include all major oil exploration, production, and pipeline operators in Alaska. ACS provides manpower and equipment to respond to an oil spill. In addition, training and research and development is carried out on behalf of its member companies.

The Task Force first met with the specific objective of developing a protection strategy for wildlife threatened by oil spills in the North Slope Region. As a starting point, the Task Force used the "Wildlife Guidelines for Alaska in the Alaska Region Oil and Hazardous Substances Pollution Contingency Plan" produced by the Alaska Regional Response Team (ARRT). The guidelines identify a three tiered wildlife response strategy:

- 1) **Primary response** - control the release and spread of spilled oil at the source to prevent or reduce contamination of potentially affected species and/or their habitat,
- 2) **Secondary response** - keep affected wildlife away from oiled areas through the use of deterrent techniques, and
- 3) **Tertiary response** - capture and treatment of oiled wildlife.

This strategy, adopted by the Wildlife Task Force, incorporates all aspects of wildlife response including; protection of critical habitat, hazing, capture and stabilization, long term rehabilitation, and release. The key components in implementing this strategy were the development of a comprehensive training program and the construction of an Emergency Wildlife Stabilization Center.

PRIMARY RESPONSE

The primary wildlife response strategy emphasizes controlling the release and spreading of spilled oil at the source to prevent or reduce contamination of potentially effected species and/or their habitat. Primary response strategies may include; mechanical clean-up, protective booming, in-situ burning and dispersant use. A review of North Slope spill response capability by the Task Force showed that equipment, manpower and techniques to handle primary response effectively, were already in place through ACS and the Spill Response Teams (SRT's) that each operator maintains. These resources are summarized in Tables 1 & 2. Collectively the equipment and manpower resources available represents one of the largest spill response capabilities in the world.

Table 1
North Slope Spill Response Equipment Summary
March 1992

	North Slope Operators	ACS	Total
Boom (ft.)	171,830	190,900	362,730
Vessels	57	27	84
Skimmers	132	66	198
Skimming Capacity (Name plate bbls/hr)	13,372	9,540	22,912

Table 2
North Slope Spill Response Personnel Summary
March 1992

	On-site	24 Hrs.	24 Hr. Total
Operator Spill Response Teams	160	160	320
ACS	11	25	36
ACS Auxiliary Contract Response Team	50	150	200
ACS Village Response Teams	—	40	40
Total	221	375+	596

SECONDARY RESPONSE

A key method for minimizing damage to wildlife, during a spill, is an effective deterrence program. This secondary response strategy concentrates on keeping potentially affected wildlife away from an oiled area through the use of deterrent techniques. Techniques may include visual methods (e.g., placing scarecrows or helium-filled balloons on oiled beaches), auditory methods (e.g., firing propane cannons or pyrotechnics), and other methods such as herding wildlife with boats, aircraft or exclusionary fencing.

To assist in the development of the secondary response, the Task Force called upon the services of Mr. Paul O'Neil, a wildlife hazing specialist from the United States Department of Agriculture (USDA). ACS employed the USDA to recommend best practical hazing techniques for the species expected as well as to develop and instruct Wildlife Hazing Training courses.

Based on identified key species (all birds, caribou, musk-oxen, brown bear and polar bear) the USDA recommended a list of equipment that would be most effective for hazing or deterrence on the North Slope. ACS subsequently ordered and stockpiled the equipment in its Deadhorse warehouse. Table 3 provides a list of hazing equipment in the ACS inventory and recommended stockpile for each SRT on the North Slope.

A consumption rate of 30 pyrotechnics per person per day was used to determine inventory requirements. It was recommended that sufficient pyrotechnics be available within the inventories of each SRT to operate a 5 man hazing team for at least a day. Additional pyrotechnics would be available from ACS which maintains 6000 rounds. This is sufficient for 20 people (utilizing ACS and SRT release equipment) to operate for 10 days at 30 pyrotechnics per day and provides sufficient lead time to have additional equipment ordered and delivered if required.

Table 3
Wildlife Hazing Equipment

DESCRIPTION	ACS	SRT
Reflecting Tape	100 rolls	20 rolls
Propane Exploder Cannons	40	3
Banger Rockets	2,000	100
Screamers	2,000	100
15mm Single Shot Pistols	10	4
12 gauge single shot full choke shotguns	3	1
Cracker Shells	2,000	100
Bear Deterrent Rounds	100	10
Scarecrows	10	—
Electric Fencing	5,000 ft.	—

To ensure personnel assigned to conduct hazing operations are qualified to safely and effectively conduct an operation, an 8 hour hazing class was developed. The class details the most effective deterrents for individual species and also provides hands-on training on how to operate the equipment. The course is instructed on an annual basis under the auspices of the ACS training program and is also put on for specific member companies upon request. The focus of the course is on tools used in hazing and how to effectively apply these tools. Also, a hands on demonstration and familiarization of pyrotechnics is provided.

Course Outline:

1. Meaning of Hazing and Exclusion
2. Reasons for Hazing and Excluding Wildlife
3. Tools for Hazing
4. Applications of Hazing and Exclusion
5. Legal Concerns
6. Interface with Rescue and Recovery
7. Safety and Communications
8. Outdoor Demonstration

Only personnel who have successfully completed the training are permitted to conduct hazing operations. As of March 1992, 44 personnel had been certified.

TERTIARY RESPONSE

Tertiary response involves the capture and treatment of oiled wildlife. Depending on the species and the degree of exposure to oil, the care requirement can vary significantly; from a simple cleaning of the outer fur/feathers to intensive longer term medical treatment (up to a month).

The Task Force considered the advantages and disadvantage of having a complete long term rehabilitation center on the North Slope versus one located in a more central location with less harsh climatic conditions. Timing of these discussions was concurrent with several independent initiatives for the establishment of a long term rehabilitation facility in Anchorage.

An initial decision was made to proceed with a capture and stabilization facility for the North Slope, as a minimum, to ensure the provision of a tertiary response capability was not delayed. Shortly after this action, the International Bird Rescue and Research Center (IBRRC) decided to establish a long term wildlife rehabilitation facility in Anchorage. Substantial financial support for this undertaking was provided by ACS, Alyeska Pipeline Service Co. and Exxon.

Development of a Wildlife Stabilization Center

The primary focus of the Wildlife Stabilization Center is the stabilization of oiled birds. The International Bird Rescue and Research Center (IBRRC), provided technical advice on the recommended size of the facility and its operating requirements. The following design criteria were established for the facility:

- Capability of handling up to 150 small birds and 200 geese at one time;
- Ability to provide on demand 106°F water continuously;
- Ability to take vital signs, do blood work, rehydrate and stabilize birds;
- Facility to be operational on short notice;
- Ability to provide long term rehabilitation for up to 10 birds;
- Ability to handle up to 10 small terrestrial mammals;
- Minimum of 6,500 sq. ft. of warehouse space;
- Maintain 75°F air temperature in the building;
- Ensure four air changes per hour in the building; and
- Operational within 24 hours of notification.

ACS designed and constructed the facility in close cooperation with IBRRC. Utilizing in-house engineering and construction expertise, ACS staff prepared a unique design consisting of two self contained air transportable modules. In an emergency, the two modules can be air lifted by C-130 Hercules aircraft. The modules were custom built at ACS facilities in Anchorage during July of 1991 and took thirteen days to fabricate. They were subsequently shipped to the North Slope, arriving in early August.

A capture and stabilization facility requires a large warehouse area for the layout of bird pens and cleaning tables. ARCO Alaska, Inc. the operator of the Eastern half of the Prudhoe Bay oil field made available a 10,000 sq. ft. warehouse as a stabilization facility in the event of a spill (Figure 1). The warehouse is normally used as a fabrication shop for operations support work. The new wildlife modules, complete with prefabricated bird pens, are permanently located in a corner of the warehouse. Within 24 hours notification, the warehouse can be cleared of equipment and materials associated with normal use, the bird pens set up and the facility made operational.

An initial concern over having the warehouse as the designated stabilization building was that it had a compacted gravel floor. The floor could not be washed down to keep it clean and minimize the risk of

disease. This problem was overcome by having an industrial pit liner (23 mil) specially fabricated for the warehouse floor. During an actual spill approximately 9,000 square ft. of the warehouse can be covered with a rolled out 60' x 150' pit liner. Two sump pumps at each side of the building have been installed to provide for draining of the floor. The pit liner is also stored permanently at the warehouse.

Wildlife Modules

The mobile wildlife treatment center consists of both a lab and utility module (Figure 2). The two modules provide 265 square feet of enclosed space. The modules are constructed with a lower steel frame, linoleum covered plywood floors, 2" x 4" walls and metal siding. The outside dimensions of each module are designed so that they are able to be placed in a C-130 Hercules aircraft and be rapidly transported by air to an emergency area. The modules are pre-wired and pre-plumbed to allow for rapid installation.

The lab module consists of a working area for veterinarians and a storage area for veterinarian supplies. It contains counter space for viewing microscope slides and conducting various tests. The lab module is outfitted with: a microwave, refrigerator, chest type freezer, centrifuge, microscope, refractometer, digital weight scale, a variety of veterinarian supplies, and fax and phone.

The utility module provides the components necessary for the design requirement of on demand 106° F water. The utility module contains the following components:

- Water softener
- Water filters
- Thermostatic water controller
- Electric booster water heater
- Commercial electric water heater
- Sump tank (80 gallons)
- Washer and dryer
- Two sinks

The plumbing design provides for delivery of water to in-module sinks and washers as well as to two external bird wash basins. Control circuits prevent operation of the system in the event of either low water or high pressure. The internal gray water tank has both a low level and high level automatic sump system.

The key component in the delivery of on demand 106° F water is the installation of the thermostatic water controller. This controller, when pre-set, insures that all required regulated water remains at 106° F. This installation frees the washers from having to regulate the water temperature manually.

The electrical scheme consists of both standby and activated circuits. The standby scheme provides heat and lighting in the facility. The activated circuit comes on line when the hot water system is in use. The activated circuit requires hooking up a 150 KW portable generator.

Holding Pens

Initial design criteria, established by IBRRC, required that each goose pen hold 6 geese and that each small bird pen hold 8 birds. The establishment of a holding capacity of 200 geese and 150 small birds required that 34 goose cages and 19 bird cages be built.

The 34 pre-fabricated goose pens are constructed of 3/8" plywood and are attached with screws to allow for easy deployment and subsequent dismantling. 2" x 2" posts provide the structural support to allow the pens to sit on the pit liner. A 36" cut-out provides an opening to place the geese in the pens. Each goose pen is designed to hold six geese. (Figure 3).

The 19 pre-fabricated bird pens are constructed of 1/4" plywood and are also attached with screws. The pen legs are constructed with 2" x 2" posts. Each pen has a bottom that is constructed of 1" diameter PVC piping that is press fit together to allow for dismantling. Netting is stretched around the frame to provide a floor. The netting is attached to screws placed at a 3"

spacing around the perimeter of the PVC frame. These pens hold 8 birds each. (Figure 4).

During activation of the Wildlife Treatment Center the pens are placed over the lined floor. A spacing of three feet between each pen allows for the convenient placing of birds and general moving about by workers. In addition, 10 small steel cages are kept in inventory for holding small oiled mammals.

Wash Area

The bird wash area consists of two externally mounted (and removable) 24" x 24" elevated rinse basins. These rinse basins are adjustable and provide for several different height settings. Both wash basins have a shower overhead. A counter with two faucets provide a place for filling the wash tubs.

Bird Care Process

A four step process is in place for handling birds (Figure 5). Firstly, oiled birds are examined at the intake table for any injury, weighed, banded, gavaged and blood samples taken. The washing process is then begun by placing the birds in four consecutive tubs of a soap and water mixture. Thirdly the birds are placed in the wash basin and rinsed for approximately 45 minutes. Finally the birds are placed in the assembled cages for feeding, drying and eventual release or air transport to the long term care and rehabilitation facility in Anchorage.

Training

Another key component in the North Slope Wildlife Response plan was the implementation of a training course designed to teach individuals the correct method of capturing and stabilizing birds.

ACS employed International Bird Rescue and Research Center (IBRRC) to develop a 20 hour Bird Collection and Stabilization Course that provides

an orientation to the operation of a major wildlife rehabilitation effort. The course is taught in two ten hour days and deals with the specifics of capture, evaluation, treatment, stabilization, cleaning, and caring of oiled birds. The use of domestic ducks provides students with hands on training.

Course Outline:

1. Animal basics
2. Capture and Handling Techniques for Ducks
3. Wildlife Rehabilitation Program Operations
4. Administrative Overview of a North Slope Major Spill Response
5. Intake and Examination Procedures
6. Written Examination
7. Evaluation

Only trained personnel who have successfully completed the above noted course will be utilized on the North Slope to fill capture/stabilization roles. Each of the Operators on the North Slope has personnel trained in bird capture and stabilization. As of March 1992, 20 personnel had been trained in Capture and Stabilization. ACS plans to continue these courses as part of its on-going training program.

Arrangements are also in place with IBRRC to provide licensed veterinarians to respond to the North Slope and assist in the operation and management of any wildlife response.

Wildlife Stabilization Center Deployment Drill

In February of 1992 ACS management designed an exercise to test its ability to mobilize and transport the Emergency Wildlife Treatment Center. The primary objective of the drill was to exercise the ability to transport the center to a remote location and additionally, to exercise the installation, hook-up and preparation for operation of the wildlife modules and support equipment at a different location.

The assistance of the U.S. Fish and Wildlife Service (USFWS) was solicited to act as auditor and also activate the drill on an "unannounced" basis. The activation was scheduled to take place between February 11, 1992 and March 13, 1992 at a time determined by USFWS.

The drill was called at 05:14 hrs on the morning of March 20, 1992. The mobilization of the modules from their residency in the U-8 warehouse to the Prudhoe Bay airstrip, ready for loading into a C-130 aircraft, took 3 hours and 15 minutes. The modules were then transported approximately 35 miles by road to the Kuparuk field where they were installed in a warehouse of opportunity and activated. From the time of arrival it took just over 3 hours to unload and reconnect the modules, bring power on line, have water brought to the facility by truck and furnished through the washing sinks at a temperature of 106° F.

A final report submitted by the USFWS indicated that the objectives of the exercise were met and the time frames in which the activities were carried out met or exceeded expectations.

CONCLUSION

Recognizing the importance of an effective wildlife response during a spill, ACS has taken specific steps to provide trained people and adequate tools to respond to potentially oiled wildlife. The success of the wildlife training program ensures that trained oil field personnel are available and can respond to wildlife in the first few crucial hours of an event.

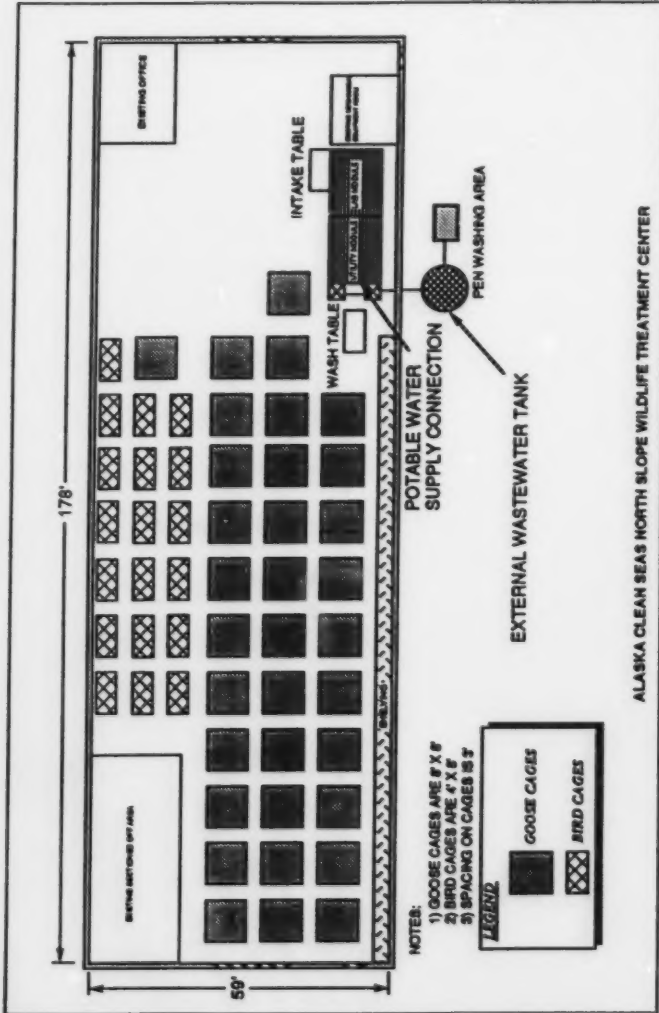
The construction of the North Slope Wildlife Treatment Center represents a substantial increase in the ability of the North Slope operators to effectively respond to the treatment of wildlife in the event of an oil spill on the North Slope. The Wildlife Treatment Center, when operated by trained personnel, provides an immediate response capability that should reduce the impact on wildlife.

Subsequent deployment exercises have shown that initial activation can be accomplished well within the 24 hour planning standard, even at a remote site, in a building of opportunity.

The mutual cooperation of federal, state and local government agencies, International Bird Rescue Research Center, Alaska Clean Seas and industry provided the varied input, both technical and operational, to ensure the implementation of a successful strategy.

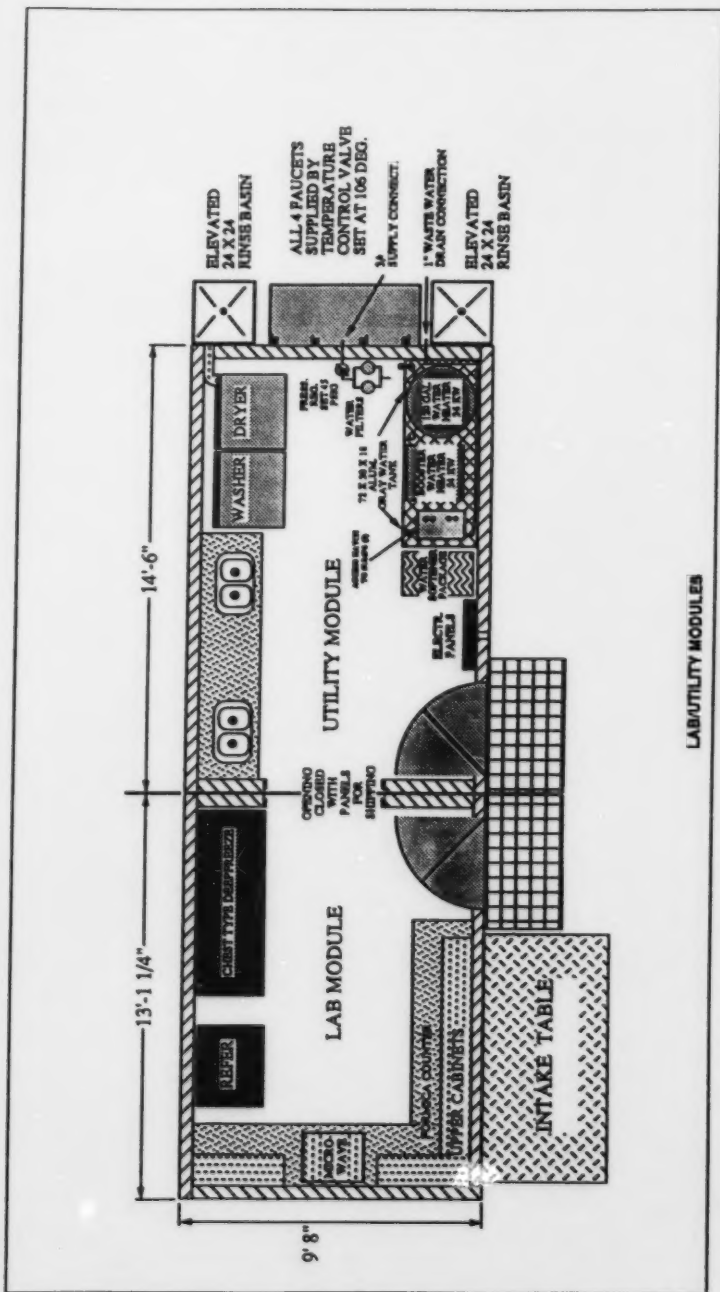
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ALASKA CLEAN SEAS NORTH SLOPE WILDLIFE TREATMENT CENTER

FIGURE 1



LAB/UTILITY MODULES

FIGURE 2

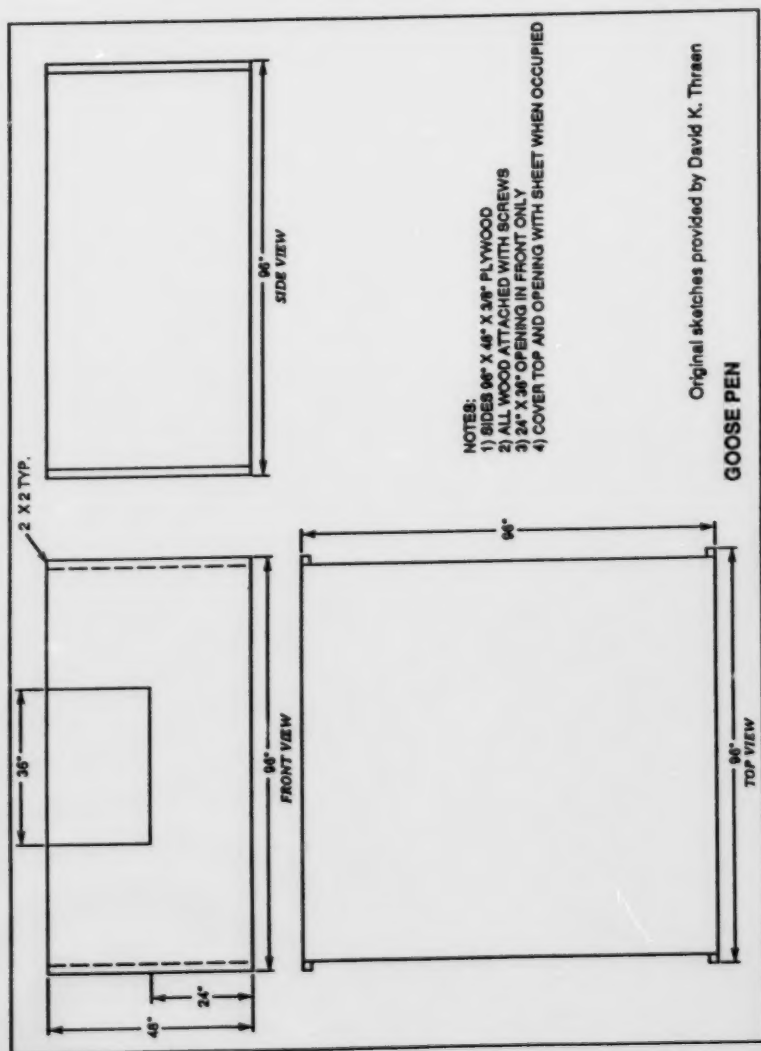
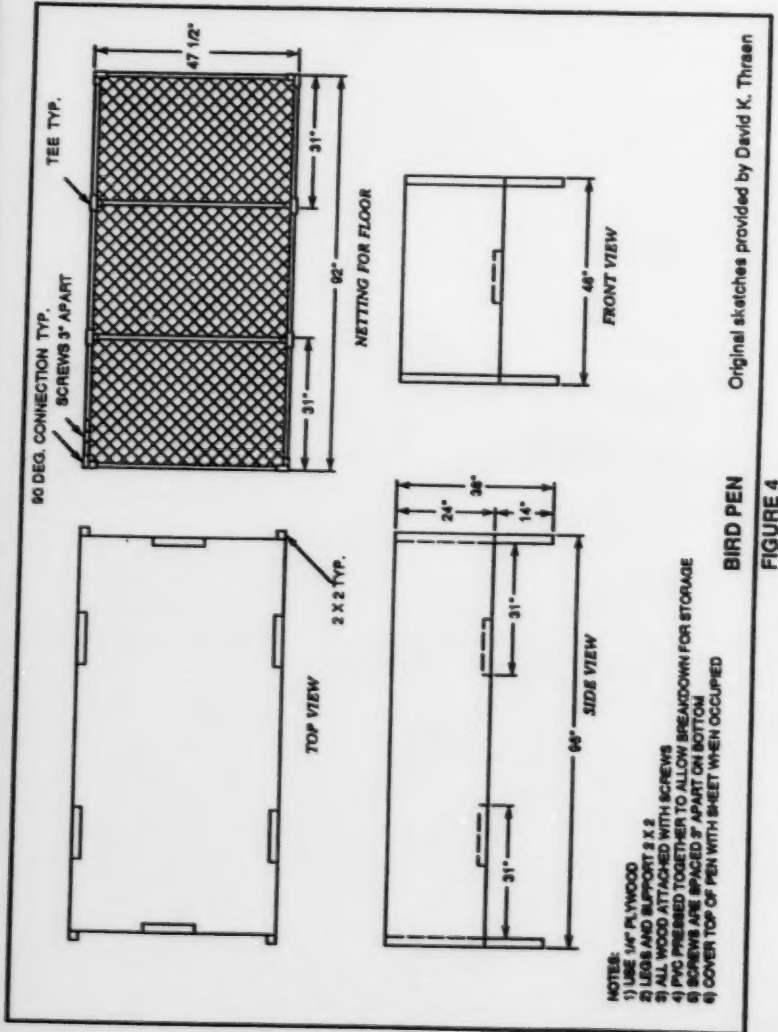


FIGURE 3



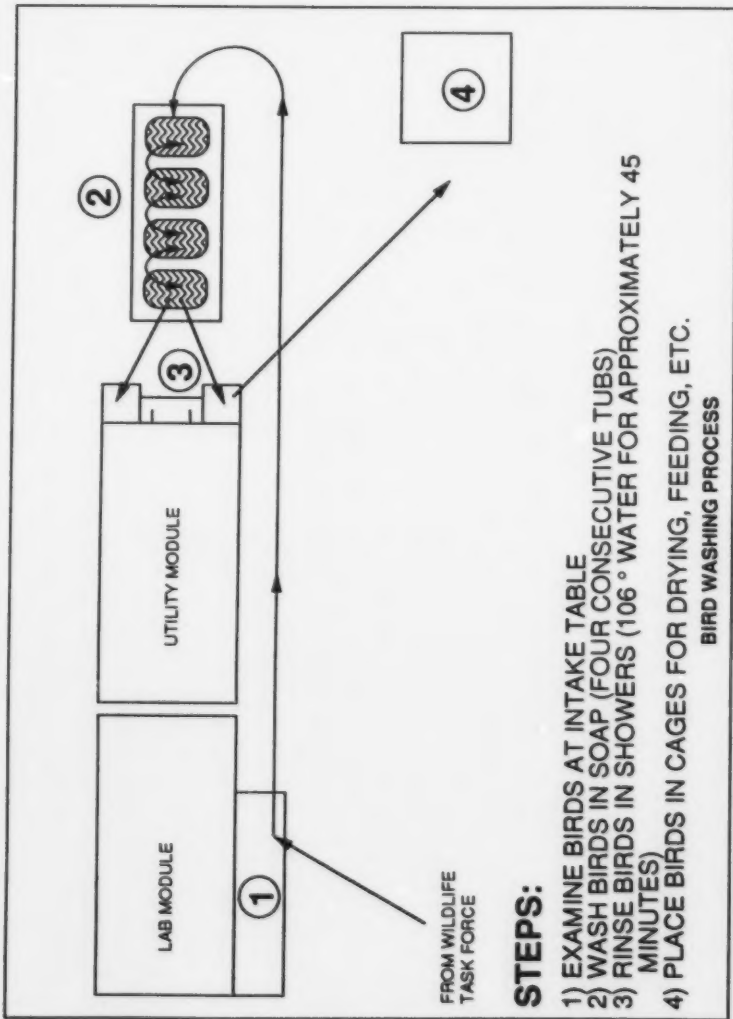


FIGURE 5

"DEVERSYS: A Decision Support System to Help in the Choice of Shoreline Cleanup Methods After an Oil Spill"

Lamarche A.¹, Emerand V.¹, Dalkir K.², Rivet C.³ and M. Fingas⁴

Abstract:

The need for a tool to speed the decision making process during oil spill cleanup has been stressed by the authorities responsible for environmental restoration. The goal of DEVERSYS, a computerized decision support system, is to recommend the most appropriate methods that should be used to ensure proper cleanup of a shoreline contaminated by an oil spill. The project involves the joint effort of the Canadian Workplace Automation Research Center (Communications Canada), the Saint-Lawrence Centre, Environmental Protection Branch and the River Road Environmental Technology Center (Environment Canada). The system combines an expert system, a data base and hypermedia technologies that simplify its use by emergency personnel. The knowledge base incorporates the knowledge of experts in shoreline cleanup from private firms (Sani-Mobile), emergencies teams (Environment Canada), and research centers (River Road Environmental Technology Center and CEDRE, France). A first prototype of DEVERSYS has been developed on a portable micro-computer with the Level 5 Object shell. The system is actually in its second prototyping phase.

Introduction

In April 1990, the Saint-Lawrence Centre started the development of a decision support system dedicated to the needs of the emergencies personnel involved in oil spill cleanup. The Saint-Lawrence Centre is a federal organization that was created to support the research and development needs of the Saint-Lawrence Action Plan, geared towards the amelioration of the quality of the Saint-Lawrence river.

The choice of the particular domain of oil spill cleanup was motivated by the following considerations:

- First, consultation with emergency personnel determined that there was a need for a practical decision support system in the field of shoreline cleanup. The system was to give recommendations on shoreline cleanup methods according to a number of factors, the main one being the restoration of lost usage due to shoreline pollution by an oil spill.

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- Potential users were both very interested and available. Indeed, the emergencies division of the Environmental Protection Branch (Environment Canada, Quebec region) agreed to spend resources on the project and to act as a pilot site for the first version of the functional system.
- Experts in various aspects of shoreline cleanup were available, and since the system to be developed needed a knowledge base on environmental cleanup procedures, the availability of expertise was essential to ensure the success of the project.
- Written documentation was also available, at all levels of complexity, from introductory manuals to more complex guidebooks.
- Finally, the knowledge domain was well delimited, so that it was judged possible to develop a functional knowledge base with less than a man/year of effort.

It was thus decided to develop a system that would provide emergency teams recommendations on the best method to be used to ensure proper cleanup of oiled shorelines. The system would also perform the following tasks:

- help establish shoreline cleanup priorities;
- help document shoreline cleanup operations;
- for archival purposes, allow storage and retrieval of data on previous cleanup operations.

Reviews show that a host of environmental decision support systems are actually under development for quite varied purposes (Hushon, 1990; Donley, 1991). Many of those concentrate on spatial data management. A few are true expert systems, giving various types of expert advice. In the domain of oil spills, the systems developed or under development incorporate numerical models, the most advanced ones integrating spatial modelling with Geographical Information System (GIS) technology (French 1991; Anderson *et al*, 1991).

DEVERSYS addresses specifically the restoration step of an oil spill, following the early response and recovery phases. To our knowledge, there was no documented system specialized in the recommendation of cleanup methods. The need for such systems, however, appears to be critical particularly for the cases of large oil spills, where the task of evaluation and survey of cleanup work has to be carried out by a host of people which do not always have the necessary expertise to make the proper decision. This was stressed by Foster *et al* (1990), on the subject of shoreline cleanup advisory teams (SCAT) during the *Exxon Valdez* spill:

"No formal training occurred; information was obtained primarily by word of mouth during one- to two-day field sessions. We do not know how this minimal introduction affected consistency among the 12-15 SCAT ecologists with varying levels of expertise in shore and oil pollution ecology. Even with better quantitative information upon which to base cleanup decisions, the ability to make the most ecologically sound decisions would have been improved by a more formal training process".

Thus DEVERSYS was designed as a performance support system, allowing less experienced officers to profit from the knowledge and expertise of seniors and helping all involved to standardize their evaluations and cleanup actions. As will be shown, DEVERSYS incorporates the latest conceptual developments in Decision Support System (DSS) technology: expert system and hypermedia capabilities.

The following organisations are taking an active part in the development of the DEVERSYS system: the Canadian Workplace Automation Research Center (CWARC, Communication Canada), furnishes expertise in the development of performance support systems; personnel of the Environmental Protection Branch (Environment Canada, Quebec region) provide expertise in shoreline cleanup and constitute the main users; the River Road Environmental Technology Center (RRETC, Environment Canada) participates in the validation process and provides expertise in shoreline cleanup; the Centre de Documentation, de Recherche et d'Expérimentation sur les pollutions accidentelles des eaux (CEDRE, France) participates in the validation process; the Saint-Lawrence Center manages the project and provides resources for the technical aspects of the systems development.

Deversys is actually under development. A first prototype has been produced for internal demonstration purposes. A functional version of the system is expected to be available at the beginning of 1993.

Material and methods

Hardware

Since the system is to be available to cleanup crews on site, the functional version of DEVERSYS will have to work on portable computers, easily carried in the field. The various hardware platforms that will be utilized by its expected users include portable PC-386 types of personal computers and Macintosh Notebooks. The user interface will have to be adapted to the black and white displays typical of small portable computers. The available hard disk space is not expected to exceed 40 megabytes.

Software tools

It was decided at the onset of development that DEVERSYS would incorporate knowledge base and hypermedia components. In order to simplify the standardization of software interfaces between hardware platforms, a windows type of Graphical User Interface (GUI) was used. The first DEVERSYS

prototype was developed on a portable PC-386 computer using Level 5 object, an object-oriented expert system shell with hypermedia capabilities.

Software engineering approach:

DEVERSYS is basically an expert system application with hypermedia components, closely related to an expert diagnostic system. Prototyping is considered the best (if not the only) approach to ensure proper development of expert systems (Hayes-Roth *et al*, 1983, Bielawsky and Lewand, 1991). A first demonstration prototype has been produced and used to test various aspects of the system.

It is expected that two more prototyping cycles will be necessary to attain a functional system.

Knowledge extraction methods

The acquisition of knowledge in the field of shoreline cleanup was done basically by consulting written documents and interviewing domain experts.

written documents:

The main written sources of documentation included basic guides that incorporated information on shoreline cleanup (Fingas *et al*, 1979; Owens, 1983; Tramier *et al*, 1987). The information contained in an Atlas produced for Environment Canada (Société d'Ingénierie Cartier, 1985; Dryade, 1986) was also used, and helped model the user interface of the first prototype. Other more specialised publications were also consulted (Harper, 1985; Hollingsworth, 1991; Hung, 1991; ITOFF, 1983; Owens, 1990; Owens and Teal, 1990; Owens, 1991; Teal, 1990)

Interviews with specific experts in various fields

Twenty one interviews were conducted with three experts. The domain of expertise covered included:

- Shoreline cleanup methods (Pierre Richard, private consultant from Sani Mobile);
- Choice of restoration methods and evaluation of the situation on site (M. Fingas, River Road Environmental Technology Center and C. Rivet, responsible for operations on spill sites at the Environmental Protection Branch)

Field visit

The Rio-Orinoco oil spill site was also visited while clean-up operations were underway, as a part of the knowledge extraction process. This visit allowed an analysis of the working methods of restoration teams on site to gather important information that can be taken into account in the final user interface. It also enhanced the understanding of the "experience" elements with the expert and enabled the development team to be more aware of the preoccupations of the people responsible for the choice of shoreline restoration methods.

Results

Demonstration prototype

A first demonstration prototype was produced after a six month development effort. This prototype incorporates knowledge on the test case of the Czan-toria oil spill, that affected the Montmagny island in the Saint-Lawrence river in 1988. The prototype allows the user to characterize the case, the affected area and the shoreline. Preliminary deductions and recommendations given by the system include a list of the main natural and human users of the shoreline, the expected natural recovery period without human intervention, the amount of cleaning necessary, and a list of applicable cleanup methods.

General system design

As described earlier, the first prototype system includes a knowledge base, hypermedia components and access to a database. The inclusion of hypermedia capabilities allowed mouse sensitive contextual help to be made available in most of the screens. This design will be maintained in the functional system.

The system is highly interactive. Basic general information on the spill are first provided by the user, such as type of oil, date of the incident, initial quantities involved and geographical area affected. Then searches are made in a database in order to access information regarding the characteristics of the shoreline and its possible users, both natural and human. This information is then displayed and validated by the user, after which an inference engine consults a knowledge base. During the inference process, other complementary information are requested from the user when needed. The system then draws conclusions and recommendations and displays them.

System outputs

After a thorough analysis of users needs, it was decided that the functional version of DEVERSYS should minimally be able to furnish the following outputs:

- Assign priorities, in the form of a code, for site cleaning.
- Evaluate the amount of cleaning needed to ensure proper restoration at each site. With each restoration level proposed, a simple and objective test will be suggested to evaluate if the cleanup is sufficient to ensure usage recovery. Examples of such tests include wiping the substrate with a clean absorbant pad without observing any oily deposit, having no pumpable oil residue on the site or leaving the site for self cleaning.
- Give an array of information on restoration methods such as a list of methods that can be utilized, a list of methods that should be avoided, the order and conditions of use of cleanup methods, the estimated length of time that the cleanup work is expected to take and technical details on the use of each cleanup method.

- Provide information on the resources necessary to ensure proper cleaning, including a list of heavy equipment and an estimate of the manpower needed.
- Finally, for special cases such as when sensitive ecological populations can be affected by the spill (for example, protected birds), the system will give instructions as to essential and urgent actions that should be taken to preserve the resource (such as scaring the birds away from the oil), even though such actions may not be directly related to shoreline restoration.

General structure of the knowledge base

Three main groups of information are used to give recommendations: the characteristics of the human and natural users of the shoreline, the characteristics of the oil affecting the shoreline and finally the physical characteristics of the oiled shoreline itself.

The general structure of the knowledge base is summarized in the following semantic network. While this model was built by compiling the knowledge extracted from the various sources cited, it is particularly dependent on the reasoning of the experts consulted.

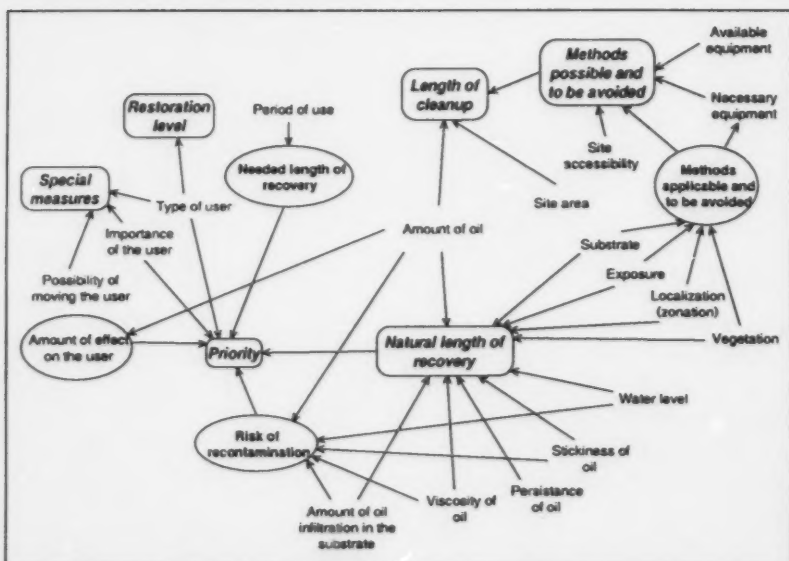


Figure 1: Semantic network showing the links between factors (text not in boxes) and goals (goals inside circles correspond to intermediate deductions. Final recommendations are enclosed in boxes).

As can be seen, a single factor can have an effect on many goals or sub-goals. For example, the type of substrate will have an effect both on the type of cleaning methods applicable to a given shoreline and its natural length of

recovery. This basic network diagram should not change significantly, even though the knowledge acquisition process is not entirely completed.

For each link in the network there is a corresponding set of production rules. An example of those rules is given in figure 2, showing part of the factors influencing the natural length of recovery of a site. The final system will use both backward and forward chaining methodology to investigate the knowledge base. Most of the work left to finish the knowledge base will consist of refining and validating the set of production rules.

IF type of substrate is straight rock and type of oil is medium and shoreline exposure is low then natural length of recovery is around 30 days IF type of substrate is cobble and type of oil is heavy and shoreline exposure is high then natural length of recovery is around 1 year

Figure 2: Example of rules assessing the average natural recovery period of an oiled shoreline. Not all possible factors responsible are taken into account.

Discussion

Preliminary assessment of the work done

The demonstration prototype has been evaluated by the main users and the experts. The general approach to system design has been judged satisfactory. There was an agreement among all users consulted that the user interface should be redesigned in order to be more practical and intuitive.

Work left

The prototype has been developed with an experts system shell that is not platform independent. Thus, the next step in system development will be to choose software tools that work both on Macintosh and PC micro-computers. The next prototype of DEVERSYS should also be fully compatible with the spatial management systems used at EPB, either through the use of the same software tools or through the development of software interfaces.

A good part of the ease of use of a system depends on the proper design of the software interface. It was thus decided that the development and implementation of the software interface would be the subject of a small applied research project conducted jointly with the École Polytechnique (University of Montreal).

The knowledge extraction process still has to be completed, and the knowledge base validated both internally and by international experts which have up to now been external to the project. CEDRE and RRETC will be particularly active during this phase of the project.

The modeling and implementation of an optimal and flexible data structure to ensure storage and retrieval of archived data still has to be completed. Programming of all the facilities to maintain the database and list its content in various formats also has to be done.

These various tasks will be done with a relatively short timetable. It is expected that a small team including a knowledge engineer, a programmer and one or two specialists in user interface, will work full time during a six to eight month period to produce a functional version of the system.

Future expected users

Consultation with all organisations involved in shoreline cleanup in the Quebec region showed that the system, once finished, would be used by their respective work teams.

Thus, future users of the system will include the Canadian Coast-Guard, the provincial authorities, the petroleum industry and the emergencies personnel of EPB (Quebec region). All those organisations will be involved in the final steps of validating the general user interface.

Expected specifications of the functional system

The functional version of DEVERSYS will be able to give recommendations on shoreline cleanup methods, will give access to historical data and will allow the evaluation of cleanup priorities. The system will include the following features:

- the capability to navigate through a series of maps, in order to spatially access various data relative to shoreline characteristics and usage, both natural and human;
- access to the inference path, allowing the user to evaluate the reason for which a recommendation was given;
- the capability to output various types of reports in order to communicate information about the state of the work at the spill site to a diverse audience;
- the capability to document the reasons for not choosing a particular recommendation as given by the system;
- provide cleanup priorities for a number of sites, located in adjacent areas;
- provide a database of oil spill cases that the user can consult during the decision making process;
- hypermedia access to informations regarding various aspects of shoreline cleanup such as ecology, detailed description on each cleanup method, images allowing the standardization of visual evaluations on the state of oiling, etc.

Issues in knowledge engineering

One very important aspect of the overall system that will be closely investigated concerns the maintenance of its knowledge base. Since most of the usefulness of DEVERSYS lies in its expertise in shoreline cleanup, procedures will have to be developed so that the knowledge base is always up-to-date.

The system will thus have to be regularly evaluated for consistency each time modifications will be made in its knowledge base. This will be done by using an array of known test cases to which additions will be made over time as need arises, or as new unexpected shoreline oiling situations occur. The reasons for any inconsistent behaviour (illogical recommendations) will have to be closely investigated, and experts will thus have to be regularly consulted to further validate the changes made to the knowledge base.

Thus, we hope to provide emergency teams with a long-lived and useful decision support tool.

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**PEAT SHORELINES
PROTECTION, CLEANUP AND DISPOSAL GUIDELINES**

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ABSTRACT

Peat shorelines are common along the margins of the Arctic Ocean and form approximately 70% of the Beaufort Sea Coast of Alaska. They consist of peat-covered beaches, beaches with peat slurries immediately offshore, peat islands and spits, tundra scarps, and low-lying peat shores. Alaska Clean Seas recently developed guidelines for spill response in this type of coastal environment. Few conventional shoreline cleanup techniques apply to peat shorelines, so that protection (containment and exclusion booming) before stranding assumes a high priority. Vacuum systems, rope-mop skimmers, sorbents (including peat itself), and manual removal can be considered for shoreline cleanup. Many peat shorelines are in an erosional state, so that natural cleaning is a viable option in many instances. Cleanup operations on peat shorelines may generate large volumes of material for disposal and in most instances combustion/incineration would be the preferred disposal method.

INTRODUCTION

Shoreline protection and cleanup manuals to date have dealt, primarily, with those types of shoreline which are common in mid- or low-latitudes. One shoreline type which has not been considered in detail in these manuals is peat shorelines, which are common in high latitudes. Alaska Clean Seas initiated a project to review the state-of-knowledge and to develop recommendations and guidelines for a response to oil spills in this shoreline environment. This paper summarizes the results of that study.

OBJECTIVES

The objectives of the Alaska Clean Seas Peat Shorelines Protection, Cleanup and Oiled Waste Disposal Response Manual are:

- to develop guidelines for the protection and cleanup of peat shorelines in the Alaskan coastal zone threatened or impacted by spilled oil; and

- to develop guidelines for the temporary disposal, transportation, and permanent disposal of oil and oiled material collected from the peat shorelines of the Alaskan coastal zone.

This is a shoreline study and does not deal directly with terrestrial or tundra peat. The guidelines developed for the Alaskan coasts are generally applicable to other high-latitude coastal environments.

PEAT AND PEAT SHORELINES

Peat is an unconsolidated deposit of semi-carbonized plant remains accumulating in a water-saturated environment. The composition of peat varies between and within deposits and a peat deposit may be classified according to the relative proportions of wood, grass, and moss. Peat forms from unaltered plant components after a limited period of initial, aerobic decay (Fuchsman, 1980). It forms in permanently wet, anaerobic (stagnant) environments, such as bogs, marshes, and swamps and typically accumulates at the rate of about 3 feet every 3,000 to 4,000 years. Water comprises 80-90% of the weight of fresh peat. When wind-dried or oiled, the surface layers of peat may be easily ignited (Mackay *et al.*, 1974). When burned, peat typically produces 2-10% ash.

The USDA (1979) recognized three basic types of peat soils (histosols):

- fibrists: fibrous peat soils consisting of mostly undecomposed sphagnum and sedges;
- hemists: semi-fibrous soils in which the plant remains have decomposed such that most fibers can be destroyed by rubbing between the fingers;
- saprists: which are amorphous and have few, if any, recognizable fibers.

The highly fibrous, organic quality of peat makes it less physically stable and more compressible than mineral soils. Peat has a bulk density as low as 1.0 g/cm³, low penetration resistance, and low shear strength. The high water content and low cohesion mean that peat can behave like a viscous liquid (U.S. Dept. of Reclamation, 1974; Donahue, 1980). The extremely poor trafficability (load bearing capacity) is important in the context of oil spill cleanup.

The peats which are commonly found at or near the Alaska coastline are illustrated schematically in Figure 1. On the North Slope, rapidly eroding tundra cliffs constitute about 70% of the coastline and this erosion of the living tundra mat supplies large amounts of peat to the coastal zone for redistribution by shoreline processes. The abundance of peat in the region makes it highly likely that peat areas would be affected by a large oil spill in the area during open water periods.

After erosion and transport, peat can be deposited on silt, sand, and gravel substrata. Peat is most often found as a mat or veneer in a dewatered state over a sand or gravel beach (#1 in Figure 2). It usually forms deposits less than 7 inches thick, which are considered relatively transient. The peat may be cut into a series of berms extending from the water's edge, where the waves may scallop the peat, to the storm berm. The backshore in northern Alaska is usually tundra with or without a low scarp. The peat may be either "breccia" (broken fragments) or "slime" in texture and appearance depending on the extent of dewatering and the size distribution of the fibers.

Peat slurry (#2 Figure 2) is found at the foot of eroding peat scarps and in the interior of low-energy coves and embayments which provide a continuous source of fresh peat. The slurry ("coffee grounds") is considered to be a relatively permanent, if mobile feature. It is usually found as a thick suspension at the water level moving with the longshore currents. The thickest suspensions exceed 1.5 feet in thickness and extend offshore for 20-25 feet. These suspensions, in a more dilute form, contribute to the organic fraction of low-energy tidal flats near barrier islands and in protected coves. Organic suspensions also may be dispersed and thus reach offshore subtidal sediments.

When deposited the peat slurry may form **splits and islands**. The open-ocean side of these features may have large deposits of dewatered peat berms (#3). The low-energy side of the islands may consist of extensive flats and suspended peat slurry. Permafrost ice may underlie the islands at depths as shallow as 11 inches. The slurry deposits are unconsolidated and impossible to walk on.

Where present, eroding **tundra scarps** (#4) may exceed 30 feet in height and are rich in organic material. Erosion takes place by wave action, ice scour, and thermal erosion, all of which undercut the scarps. A living tundra mat usually overlies thick peat deposits. These scarps tend to slump and form a gently sloping peat talus to the water's edge. Thick peat deposits may be found at the base of the scarps, and these take any of the previous three forms. Polygonal tundra mats may subside due to permafrost thaw, forming a very complex shoreline with pools underlain by decomposing vegetation. This process in low-energy areas may bring freshwater-adapted living plants into contact with saline/brackish water.

Low-lying peat shorelines can occur also on open tundra or lagoon coasts without the presence of a tundra scarp. Under these circumstances, there will likely be less clastic sediment on the beachface, thus potentially compounding oiled shoreline interactions with peat. Access to peat-covered beaches is difficult due to the low shear strength and penetration resistance of peat.

BEHAVIOR OF OIL ON HIGH-LATITUDE PEAT COASTLINES

On **peat-covered shorelines**, heavy oils will not penetrate far into the peat, even when the peat is dewatered and surficially dry. Lighter oils and refined products,

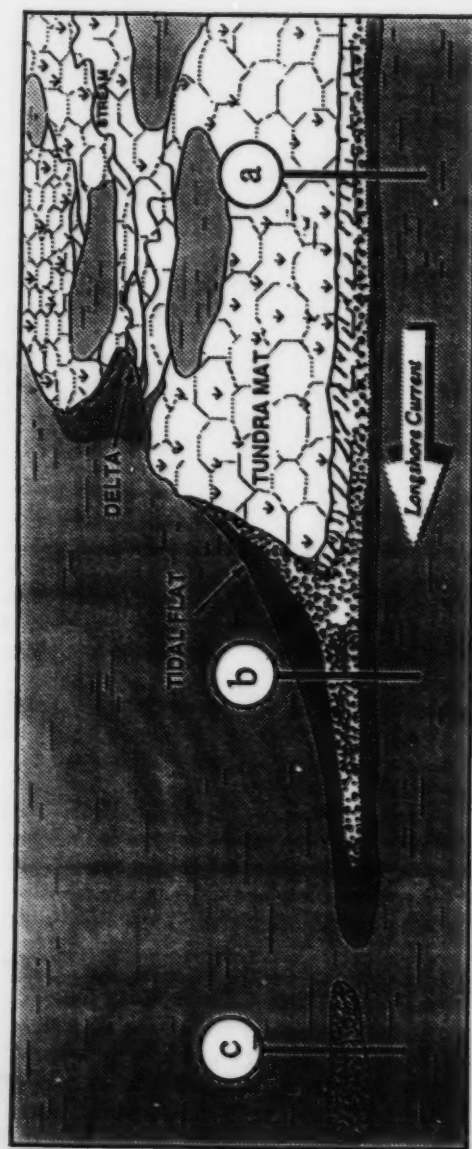


FIGURE 1
TYPICAL ARCTIC PEAT COAST:
CROSS-SHORE PROFILES (a-c) ARE DESCRIBED IN FIGURE 2

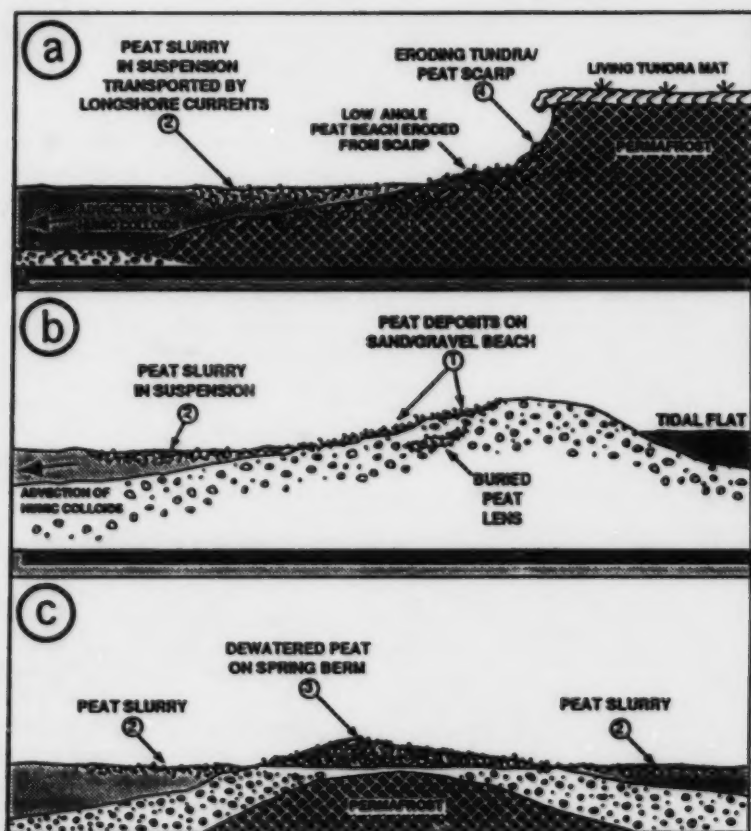


FIGURE 2
CROSS-BEACH PROFILES THAT ILLUSTRATE THE VARIOUS FORMS
IN WHICH PEAT OCCURS IN THE SHORE ZONE

however, will penetrate further, and possibly have a longer residence time. Heavy oils can persist when buried by sediments or by new peat deposits. The whole deposit will have a similar oil residence time to that of the sand-gravel beach. Complete oil removal may be delayed until a storm/storm surge.

Biodegradation of oil in peat deposits should proceed much more slowly than on sand and gravel beaches. Peat creates a high oxygen demand, depleting oxygen in pore waters, and decreasing the rate of oil degradation. *In situ* biodegradation may not proceed rapidly as on sand and gravel shorelines.

Oil may become incorporated into a peat slurry by mechanical or chemical dispersion of floating oil, by reworking from the shoreline with or without included sediment, or by evaporation of low-molecular weight hydrocarbons, causing the oil to sink. Peat slurry will probably have some upper limit of oil sorption (dry peat can sorb 3-10 lb oil/lb peat dry mass), at which point oil will be released from the slurry. Oil-coated peat fibers and humic colloids will tend to move to areas of low wave-energy (offshore, below wave base, or in tidal flats). Turnover of peat slurries will occur slowly except in storms when large inputs of fresh peat will be contributed by tundra erosion. This will remove most of the oil and dilute the residue, but in the meantime the peat slurry provides shelter to the intertidal area by attenuation of wave action. This has the effect of increasing oil residence time.

Behavior of oil will depend on whether the oil is stranded on the exposed or sheltered side of the island or spit. On the open-ocean side, the behavior will be similar to that of oil on peat-covered beaches, whereas on the lee side oil behavior will be affected more by the morphology and rheology of the peat slurry.

Oil behavior on a tundra scarp will be influenced primarily by the height of the oil on the shore, in addition to other factors such as the sediment grain size, wave fetch, and the type and volume of the oil. The extent of dewatering of the peat facies on the shoreline is likely to be greater on the upper shore. Penetration and retention of the oil will be greater where the peat is dry or fractured. If oil is deposited beyond the storm berm or over the low tundra scarp, oil residence time in the absence of wave and tidal action will be extended. On the beachface, the sediments, inshore water depth, and wave fetch and fetch window are more important as factors affecting oil residence time. Overall, the rate of tundra scarp retreat may be sufficiently high (30 feet/yr) as to preclude any concerns over lengthy oil residence time (Owens, 1985).

The likelihood of oil stranding above normal high water on low-lying peat shorelines is increased by storm surges. On the Beaufort Sea Coast of Alaska during storm surges, east winds lower the water level, whereas a west wind may strand oil and debris several thousand yards inland. During easterlies the meteorological "tide" will temporarily put at risk the shallow subtidal (Owens, 1985).

POTENTIAL PROBLEMS FOR PEAT SHORELINE OPERATIONS

In common with many arctic and subarctic shorelines, peat beaches may be remote and climatically harsh. Sea ice cover and the development of an ice foot

from frozen wave spray may prevent access to the oiled beaches, even if weather conditions are suitable for an oil spill response. The most feasible and practical peat shoreline cleanup techniques are those for which the equipment and personnel can be transported easily by helicopter. In a very large oil spill, barges could be used for access, unless operations were delayed until after freeze-up, when the trafficability of the peat would improve.

Fragmented, slumped peat blocks from the tundra mat are broken and irregular in morphology. Oil may penetrate into the dewatered, surficial layers. Pools of oil and chocolate mousse can also accumulate in the spaces between and beneath blocks. This oiling condition is highly probable at the top of the shore where both stranded oil and blocks of eroded tundra mat tend to accumulate.

Water-saturated peat has little penetration resistance or shear strength, so that trafficability may be negligible, even for foot traffic. Land-based operations are also complicated by the fact that almost any traffic will mix oil downwards into the peat.

The use of "sausage/pom-pom" sorbent booms at the shoreline tends to be essentially a manual technique. The use of squeegees, rakes, hand-rollers, and shovels is also likely to have a very low oil-encounter rate. Mechanical or hydraulic recovery techniques are unlikely to be successful except in areas with good access from sea or land, a firm sediment substrate, and high volumes of oil.

Recovery of large volumes of oil will also involve an effective temporary storage, collection, transport, and final disposal operation. Unfortunately, a great proportion of the oily material recovered by vacuum, hydraulic or mechanical techniques will be mixed with seawater and peat. Dewatering is strongly recommended to reduce the volume of waste material. This is best accomplished at or near the recovery point.

PROTECTION TECHNIQUES

The range of applicable offshore and nearshore techniques for shoreline protection is summarized in Table 1. These techniques for use on peat shores are similar to those used to protect other types of coast:

mechanical/combustion techniques. Containment near the source is the preferred mode of protection. If currents exceed 0.7 knots, however, boom configurations must be diversionary, and booms become ineffective in currents of more than 4 knots. Thick slicks of product and fresh crude oil can be burned at sea under some conditions; and

chemical agents. Dispersants applied before the spilled oil becomes emulsified and loses volatiles can be effective under the proper circumstances. Dispersants can have toxic effects on biota in water depths less than 30 feet and should be avoided near peat slurries and in deltas, lagoons, and tide flats.

TABLE 1
RECOMMENDED PROTECTION AND CLEANUP METHODS FOR PEAT SHORELINES

PROTECTION/ CLEANUP METHODS	PROTECTION		CLEANUP				
	Offshore	Nearshore < 15 Feet	Peat-Covered Beaches	Peat Slurry	Peat Islands Spits	Tundra Scarps	Low-Lying Peat Shores
Booms / Skimmers	P	P	-	V	-	-	-
Incineration - <i>In Situ</i>	VP	V	V	A	A	A	A
Chemical Dispersants	VP	V	A	A	A	A	A
Herders / Elastomers	NA	V	A	A	A	A	V
Vacuum Recovery	V	PV	V	P	P	V	V
Low-Pressure Flushing	-	-	P	A	P	P	V
Sorbents	NA	NA	V	P	V	V	V
Manual Methods	-	-	VP	V	V	V	V
Substrate Removal	-	-	V	P	NA	NA	A
Natural Recovery	V	V	PV	PV	PV	PV	PV
Bioremediation	NA	NA	V	A	V	V	V

P = PREFERRED

V = VIABLE

NA = NOT ADVISABLE

A = AVOID

- = NOT APPLICABLE

Operational Constraints to Avoid Damage

To prevent damage from shoreline protection measures using booms and skimmers, the emphasis of the operation should be to keep personnel and equipment off the shore as much as possible. For example, when shorefast diversionary booms are deployed, the exact anchoring points will likely be on a sediment shoreline. This is helpful, not only because the anchor is probably more stable there, but also because trampling damage to peat islands or spits will be avoided. If the latter must be used, because of the coincidence of shoreline oiling and the spits/cusps/headlands which are acting as natural collection points, the deployment should be designed to limit trampling.

Vacuum pumping and removal by skimmer are not damaging to the marine environment, unless, for example, inappropriate treatment of separated water after demulsification is undertaken. However, there are operational constraints on shoreline-based recovery activities, and these are as described above for oil containment operations.

Burning of oil contained in fire-containment booms is possible in calm water and winds of up to about 17 knots or in fissures in the ice. Oil must be burned a safe distance from vessels, structures, and other sources of fire hazard. Offshore burning may affect coastal communities much less than burning oil and or oily waste onshore. There is a temporary degradation in air quality. Soot produced by burning crude oil is approximately 5-20% by volume, depending on burn area and oil type. Post-burning activities include recovery and disposal of burnt oil residues (solids).

CLEANUP TECHNIQUES

The type and volume of oil spilled have a major influence on the choice between the different cleanup techniques. In general, the heavier and more weathered the oil, the less effective will be techniques involving booms, skimmers, and vacuum systems. However, low-pressure flushing and the use of sorbents may be equally effective on more weathered or emulsified oils. Conversely, manual methods such as the use of squeegees, rollers, shovels, and rakes will be less effective on light products and on large spills. Recommended shoreline cleanup techniques for the different types of peat shoreline are summarized in Table 1.

Vacuum systems, booms, and skimmers in combination can recover deep pools of mobile oil if the oil is not too full of debris. Rope mops could be used to recover free oil in peat slurries. These techniques are applicable for shoreline cleanup provided the oil can be concentrated into layers thicker than about 0.02 inches and provided the oil is not full of debris nor too viscous. Thick pools of oil stranded in lagoons or among slumped tundra blocks on scarp-foot beaches are particularly responsive to quickly-deployed vacuum systems. Rope mop skimmers may be very useful in situations where peat slurry prevents use of oleophilic disc skimmers. Brown and Goodman (1989) describe the use of nets

for controlling bitumen in marine environments. The peat slurry would be less viscous than the bitumen in their experiment but using a finer mesh than the 1/4" mesh used by Brown and Goodman could probably compensate for this viscosity decrease.

The objective of **low pressure flood and flush** is to raise the local water table to float oil down shore and into a boomed area for collection by the above methods. This method would probably erode large quantities of peat from beaches and might not be as effective as on a mineral beach. Water pressure must be low enough to prevent sediment erosion. It is likely that peat will be remobilized in large quantities using this technique. Customized net panels in shorefast booms would help retain oiled peat slurries.

Sorbents, such as peat itself, are effective for fresh crude and product. The most effective technique in a peat-rich environment might be to use natural peat as a sorbent and remove the most heavily oiled fraction. A laboratory study which tested 21 oil spill sorbents (Environment Canada, 1978) demonstrated that for peat moss, which tends to be naturally oleophilic, the effectiveness on fresh crude and fuels (weathered for 1 day) exceeded the effectiveness on aged oils (weathered for 7 days). However, this study was carried out on a dry peat moss. There is a tendency for the peat moss to become less oleophilic when wet. Nevertheless, the peat moss remained floating during the 48-hr test, and was effective for all types of oil except for the Bunker C, with which there was some sinking of oiled sorbent. This has been a traditional flaw in the use of loose natural sorbents, and, if it occurs, renders the oiled sorbent less recoverable than the oil. In peat-dominated areas, there may be no additional impact in failing to recover all the sorbents provided peat moss is used and provided the most severely oiled patches of oiled peat are recovered.

Manual methods could remove the most oiled portions of peat mats with raking and tilling of any remaining materials to speed physical and biological cleaning processes. Oil penetration into the peat mat is likely for most types of oils and peats, so that often there may be relatively little recoverable oil on the surface of the peat. The load-bearing capacity of peat shores is low during the open water season but increases following freeze up. For summer cleanup, crews could use plank walkways or snowshoes to minimize damage and trampling. Progress on the shore is inevitably very slow and, following the "Exxon Valdez" spill, careful removal by a crew of 10-12 skilled people required about 5 working days for an area of oiled, firm peat extending over about 4500 square feet in Prince William Sound.

Direct removal of peat and peat slurries could be beneficial under some conditions. Peat could be stacked and dewatered before being moved to a disposal site; and

Natural recovery is often the least costly and least damaging alternative for treating light and moderate oiling in inaccessible areas. Peat shorelines of the

Beaufort coast are eroding at rates which reach 30 feet/year in some areas, and oil is likely to have a short residence time in these areas. Custom fertilizers could be added to oiled peat to increase biodegradation rates if nutrients limit degradation rates; in many cases, however, low oxygen levels will have a greater effect than lack of nutrients, and fertilizer application may not increase the degradation rate.

The shallow near-shore water common in the Beaufort Sea may require that some areas of shoreline are cleaned up with access from land. This would necessitate greater support from larger helicopters, and additional hardware in the form of temporary accommodation (at least for equipment) and possibly temporary roadways. Operations might include the use of Rolligon equipment outfitted as dump trucks, front end loaders, back hoes, and fork lifts. This equipment can travel modest distances along the coastline in the summer months without encroaching on the tundra. They can be used in tundra areas with limited or no damage if traffic is minimized, and could prove extremely useful following freeze up when the tundra becomes much less fragile.

Operational Constraints to Avoid Damage

Many of the potential constraints on cleanup of arctic and sub-arctic peat-dominated coastal ecosystems are general:

- avoid trampling vegetation and the use of heavy machinery (likely to incorporate oil deep into peat);
- use shallow draft boats and ATVs;
- minimize substrate removal and vegetation cropping unless very heavily oiled;
- avoid use of chemicals and nutrients where oil is thick and recoverable, or in shallow water (less than 30 feet deep);
- recover all sorbents and cleanup debris;
- control litter from cleanup teams;
- avoid raking loose sorbents/peat slime on living bog plants;
- minimize use of steam (damages biota), noisy equipment and over-intrusive cleanup and surveillance methods (e.g., low-altitude helicopter overflights);
- prevent labor force from wandering inland during rest breaks;

- reduce soil/peat erosion by using only low-pressure hydraulic flushing techniques;
- avoid burning peat or oiled debris near living plant communities or upwind of human habitation;
- manual oil removal, recovery of sorbents and flushing, although recommended methods, are also likely to promote foot traffic in peat areas;
- drainage and nutrient application to low-lying peat shorelines during cleanup reverses the conditions responsible for peat formation;
- if removal of peat on sediment is required, only the top 1-2 inches should be picked up; and
- minimize construction of temporary camps and dirt roads, since these will destroy bog communities, impact drainage, and if cleanup is prolonged, may affect permafrost.

The remoteness of many potential spill sites more or less requires a large-scale operation, even for relatively small oil spills. Access by barge is limited to open-water months, whereas some helicopter and Rolligon supported operations could continue following freeze-up until cleanup is complete. Many operations in the Arctic are better conducted during the winter: migrating wildlife are absent, the tundra is frozen and less fragile; ice roads can be constructed on the sea ice and tundra with little environmental damage; and consolidation of the peat could facilitate careful mechanical removal. Any unrecovered oil in the Fall would need to be carefully mapped and its location documented to facilitate winter operations and to predict its probable location the following spring.

OILED PEAT DISPOSAL GUIDELINES

Disposal of collected oil, oil/water mixtures, oiled debris and oiled peat will be an ongoing activity during an extended cleanup operation and the final step of a spill cleanup operation. Disposal problems can be complicated by (1) the large quantities of different materials that may be involved, and (2) the logistics of handling and transporting the materials between the various recovery sites and disposal sites. Regulatory approvals would be required for combustion methods, land disposal and central storage locations.

Disposal of oiled materials is commonly a major problem. Quantities of oiled debris can be quite high in the event of a major spill, and the most cost-effective alternatives will be those which minimize transportation and processing.

When selecting a disposal method for a particular material there are three key factors to be considered:

- efficiency: the selected method should involve a minimum of handling, transfer, and storage;
- effectiveness: ensure that using the selected method will work within the stated goals and will not pose further environmental, health or safety problems; and
- approvals: selected methods must comply with applicable government standards and regulations

The choice of which method to use for a particular material will generally be based on five parameters:

- oil type and viscosity
- amount and nature of debris
- spill size
- local environmental considerations
- regulatory standards

The following disposal options are available for liquid oils as a function of oil type and viscosity:

1) for light and medium oils (fresh crude, diesel), flowing emulsions:

- all disposal techniques may apply;
- reprocessing is a preferred alternative, if the oil is relatively debris-free and refining facilities are available locally;
- combustion is also highly applicable; and
- demulsifying processes and/or chemicals should be considered for emulsions.

2) for heavy oils (weathered emulsions, Bunker C):

- demulsifying processes and/or chemicals should be considered for emulsions;
- reprocessing may apply for debris-free fluids;

- landfilling may apply; and
- certain incinerators may apply.

In situ burning, nozzle-type burners and natural degradation are not recommended for heavy oils. Experience with these oils shows that they are extremely difficult to ignite, and that once ignited the flames are quickly quenched when the oil is emulsified. Burning is not practical, therefore, for heavy, emulsified oils.

There are three basic methods for disposal of oil-spill wastes (Table 2):

biodegradation is a technique which relies on the natural degradation of the oil by microbial activity under oxygenated conditions. This process is slowed in the Arctic by low temperatures. Decomposition rates could be increased using an insulated system to cycle nutrient and oxygen-enhanced water through oiled peat; biodegradation may include **burial/land tilling/or injection** which could be used for disposal either at the affected site or at an existing facility. A potential concern for this method would be the potential for contamination of surface water or groundwater. The rate of biodegradation in peat-rich sediments is likely to be less than in mineral sediments under the same conditions since degradation of the peat will compete with degradation of oil for available oxygen and nutrients.

combustion methods are available for both liquid and solid spill wastes, and might be the preferred method for disposing of combustible material. Commercially available equipment can be used such as high-volume flaring systems, atomization techniques, rotary cup burners, incinerators, burn barrels, rotary and reciprocating kilns, (combustion techniques are subject to air emission standards),

reprocessing of waste at existing facilities can include disposal at petroleum facilities, including reprocessing, reclaiming, recycling, well injection and combustion. In many cases this may not be feasible because of water and debris in the recovered material

Where oiled debris is present in the material that requires disposal, the use of landfill sites and/or incinerators are most applicable. Table 3 lists the calorific value (heat of combustion) for 13 peats found in the U.S. Table 4 compares the combustion characteristics of a variety of debris that have been successfully combusted at past spills with the characteristics of peat with a range of oil contents (Environment Canada, 1978; S.L. Ross, 1988). By comparing the data in Tables 3 and 4 it may be concluded that peat is an excellent candidate for disposal by combustion. In fact, peat has been used in the past as both a sorbent and a combustion promoter (Environment Canada, 1972). It should be noted that peat will burn more easily when at least partially dewatered (6-20% water).

TABLE 2
RECOMMENDED OILED PEAT DISPOSAL METHODS

DISPOSAL METHOD	TYPE OF OIL/OILED PEAT WASTE MATERIAL				
	LIGHT TO MEDIUM OILS (fresh crude, diesel)	HEAVY OILS (weathered emulsions, Bunker C)	COMBUSTIBLE OILED DEBRIS (logs, sorbents)	PEAT SLURRY (slimes, or broken fragments)	NON-COMBUSTIBLE DEBRIS OR SEDIMENT
Biological natural degradation	V	A	V	V	V
burial	A	A	V	NA	V
landfill	V	V	V	V	V
Combustion	PV	V*,A	P	P	V*
Disposal At Petroleum Facility reprocessing	P	V	A	A	A
reclaiming	V	A	A	A	A
recycling	V	V	A	V	V
well injection	V	A	A	A	A
demulsification	V	PV	A	NA	A

P = PREFERRED

NA = NOT ADVISABLE

A = AVOID (or not feasible)

* Certain incinerators may apply

TABLE 3
ANALYSES AND CALORIFIC VALUES OF AIR-DRIED PEAT

Kind of Peat	Locality	Water (%)	Ash (%)	Sulfur (%)	Calorific Value (BTU/lb)
Brown, fibrous	Fremont, NH	6.3	7.93	0.69	9,300
Brown, fibrous	Hamburg, MI	7.5	6.55	0.28	9,100
Light brown	Rochester, NH	11.6	4.06	0.22	9,100
Dark brown	Westport, CT	12.7	4.12	0.24	8,600
Brown, fibrous	Westport, CT	19.7	3.23	0.19	7,700
Brown	Kent, CT	12.1	7.22	0.83	7,700
Brown, fibrous	Cicero, NY	14.6	7.42	0.25	7,600
Brown	Black Lake, NY	8.7	16.61	0.99	7,500
Brown, fibrous	La Martine, WI	9.9	16.77	0.79	7,500
Salt marsh	Kittery, ME	13.5	12.04	1.94	7,300
Black	Greenland, NH	6.6	24.11	1.01	7,200
Brown, fibrous	Madison, WI	7.0	18.77	0.38	7,000
Brown, sandy	Kent, CT	9.1	36.06	1.46	5,950

[adapted from Perry, 1941]

TABLE 4
CALCULATED CHARACTERISTICS OF OILED COMBUSTIBLE DEBRIS

Debris Type	Oil Content (wt %)	Bulk Density (tons/yard)	Net Heat of Combustion (BTU/lb)	Ash (wt %)
Oiled Shore Vegetation	10	0.08-0.17	4,750	5
Oiled Seaweed	10	0.69	3,225	5
Oiled Driftwood	10	0.25	9,000	1
Oiled Rubbish	10	0.13	6,925	20
Oiled Poly. Sorbents (saturated)@	90	0.46	1,525	0
Oiled Peat	10	0.08-0.17	8,150	4-35
Oil saturated/wet #	NA	0.17-0.34	11,200	2-17
Oil saturated/dry *	75	NA	29,400	0.7-6

Notes: @ 10 lb oil/lb sorbent;

#: 6 to 20% water;

*: 3 lb oil/lb peat;

NA: not available

[adapted from S.L. Ross, 1988]

CONCLUSIONS

The successful cleanup of oil, on peat shorelines, face a number of difficulties:

- remoteness and accessibility, particularly in the winter;
- surges that could deposit oil above the range of normal wave action;
- peat often forms blocky, broken, irregular shorelines which would pool oil and be difficult areas in which to work;
- standard mechanical and hydraulic recovery techniques used on mineral shorelines could be of limited effectiveness; and
- the difficulty of removal of oil from oil/water/peat suspensions and slurries.

The protection alternatives for peat shorelines are similar to those used in other coastal environment and lower latitudes. The only difference for this shoreline system comes into play when the protection operations involve land-based deployment. In these instances particular care is necessary to avoid damage at the shoreline.

The cleanup alternatives for peat shorelines are constrained by the nature of the oiling conditions and the very low bearing capacity of the shore-zone materials. In general, flushing techniques, vacuum recovery and natural recovery are the preferred options. Again, the key factor in all onshore operations is to minimize the damage that foot or mechanical traffic can induce at the shoreline or in backshore staging areas. Many peat shoreline are naturally erosional, so that the expected persistence time at most locations would be short.

The disposal alternatives include:

- biological methods, such as natural degradation on land, burial, and landfilling
- combustion methods, such as high-volume flaring systems, atomization techniques, rotary cup burners, incinerators, burn barrels, rotary and reciprocating kilns
- disposal at petroleum facilities, including reprocessing, reclaiming, recycling, well injection and combustion.

Peat shorelines are a common occurrence on many high latitude coasts, as well as in other parts of the world. They are physically different from sediment or bedrock coasts due to the very unconsolidated, low-density nature of the material. Spill response is possible and practical in this environment and can be successful provided that the basic concepts of damage minimization are followed.

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